Numerical analysis of the effect of underpass construction on an existing bridge foundation

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Abstract. Micropiles are used effectively in many ground improvement applications, such as increasing soil bearing capacity, reducing the settlement of existing foundations, strengthening existing foundations, and reducing lateral soil movement due to arching. In this research, the micropiles, a geotechnical supposed solution, have applied to maximize the benefit for all the mentioned features. The frictional resistance between the surface of micropiles and the surrounding soil is considered. Besides, the effect of the micropiles network is considered as a possible means for improvement. We have examined a case study in which micropiles of 400 mm diameter and 13.00 m length were used to improve the bearing capacity of soil underlies the existing bridge foundations, reduce their settlement, and decrease the side-support system's deformation. The models created for this study were used to simulate the proposed geotechnical solution.

1. Introduction
The new Al-Nasser Road in Riyadh, Saudi Arabia, intersects with the existing Al-Haeer Road, as shown in Figure 1. There is an existing bridge along Al-Haeer Road at this intersection. A new underpass is to be constructed along Al-Nasser Road as a traffic solution for this intersection and will comprise two different sections. The first section is the open excavation part at the start and end of the underpass. The second is the intersection zone with the existing bridge along Al-Haeer Road, which requires a side-retaining system to support nearly 10.00 m high ground materials, as shown in Figure 2.
The effects of the excavation and the construction of the side-retaining system on the existing bridge foundations must be studied to ensure the bridge's foundations' long-term stability. It has been suggested that micropiles be used around the bridge's existing foundations to minimize the resulting settlement of the bridge foundations due to the construction of the underpass, as shown in Figure 3. Thus, two numerical models were created to simulate the second section of the underpass, one with micropiles and the other without micropiles, to ascertain the effects of using them.
Figure 3. Proposed geotechnical solution for the existing bridge foundations. (a) Modified design of the underpass; (b) details of using a micropile wall around the existing foundation

Micropiles have been used effectively in many applications of ground improvement. [1] Moreover, [2] showed that micropiles create an in situ coherent composite reinforced soil system. The engineering behavior of micropile-reinforced soil is highly dependent on the group and network effects that influence the overall resistance shear strength of this composite system. [3] presented an excellent state-of-the-art review, covering all studies of and contributions to the use of micropiles. These authors also reviewed
the geotechnical design guidelines in different countries for axial and lateral load capacities and the methods used for motion estimation. [4] studied the skin friction and bending stiffness of micropiles, which are sufficient for increasing bearing capacity. [5] carried out numerical simulations to examine the improvement in the load-deformation response of sand due to the densification of the soil surrounding micropiles and the interaction between the soil and the micropiles. They showed that fixing the micropiles in the ground close to the foundations significantly improved the foundations' bearing capacity. [6] investigated a case study in which micropiles were used to improve the soil's bearing capacity around the foundations and in the rehabilitation of the total building foundation system. [7] conducted a field study to investigate the load transfer mechanism during the connection of micropiles to the concrete plate under the initial load and additional loading. [8] carried out a numerical analysis of the results of bearing capacity studies of sandy soils. The use of micropiles led to an increase in the bearing capacity of loose sandy soils of up to 100. [9] studied the numerical model that was developed to evaluate the skin friction of micropiles embedded in gravelly soils. Ultimate skin friction capacity increases due to an increase the angle of shear resistance of the soil for micropiles embedded in gravelly soils. Besides, for a constant diameter, increasing the length of micropiles embedded in gravelly soils, which automatically increases the slenderness ratio, increases the ultimate unit of skin friction. [10] described the results of a case study on using 350 micropiles to improve loose sandy soil deposits. They evaluated micropile injection effects on liquefaction remediation and the improvement in soil stress–displacement behavior. [11] studied the load transfer mechanism of micropiles in weathered rocks. A 3D numerical model was developed to understand the behavior of micropiles in this situation. In the present study, two finite elements (FE)-based models were created in order to simulate the construction of the underpass, the path of which will meet the bridge's existing foundations. It has been suggested that a network of micropiles be constructed around the existing bridge foundations to minimize the effects of construction. Thus, one model simulated the underpass construction without a network of micropiles around the bridge foundations, and the other model simulated the construction of the underpass with a network of micropiles around the bridge foundations. The results of the two models were compared to decide the efficiency of the proposed geotechnical solution.

2. Geological study of the site

According to the geological map of the project area [12], the region where the site is located belongs to the upper breccia complex (Ja+Jha) – solution breccia comprising carbonate facies of Arab-B and Arab-A members, mixed together with collapsed blocks from the overlying Sulaiy Formation after the solution of evaporitic (anhdydrite) facies of Arab-C and Arab-B members and Hith Anhydrite. Hith Anhydrite (Jha) is composed of massive bluish-grey translucent anhydrite at Dahal Hit (see Figure 4). The typical ground profile of the site is shown in Figure 5.

![Figure 4. Geological map of the site](image-url)
3. Numerical modeling

The 3D finite element software PLAXIS 3D V 2013 [13] and manual were used to create the models to simulate the underpass construction through Al-Nasser Road, which will affect four bridge foundations Al-Haer Road. Because of the underpass's geometrical symmetry and to reduce the analysis time, only half of the geometry was simulated (i.e., the effect of underpass construction on two bridge foundations only). Figure 6 shows the general configurations of the full path of the underpass. Figure 7 illustrates the main difference between Model 1 and Model 2, which is the presence of the micropiles around the bridge foundations in Model 2.
For the retaining secant pile walls, the piles' proposed configuration is 20 m in length, 1.0 m in diameter, and with a 1.2 m spacing between the centrelines of the piles. The secant piles were simulated as a plate element with an equivalent thickness that yields to the same moment of inertia as the secant piles.

For the micropiles proposed as a solution to reduce the bridge foundations' settlement in Model 2, the proposed configuration of the piles was 13.0 m in length, 0.4 m in diameter, and with a 0.5 m spacing between the centrelines of the micropiles. Micropiles were simulated as a plate element with an equivalent thickness that yields to the same moment of inertia as the micropiles. The groundwater table (GWT) was encountered at a depth of 2.5 m below the ground surface.

Model 1 comprised two major structural elements, the bridge foundations, and the secant pile wall. Both structural elements were simulated as plate elements. The properties assigned to both elements are the concrete material properties ($E = 2 \times 10^7$ kPa, $\nu = 0.15$). The thickness of the bridge foundations was 1.5 m. The plate elements' equivalent thickness that yields to the same moment of inertia as secant piles are 0.843 m.

Model 2 comprised three major structural elements, the bridge foundations, the secant piles, and the micropiles are surrounding the bridge foundations. The bridge foundations and the secant piles were simulated as in Model 1. The micropiles were represented as a plate element with an equivalent thickness of 0.311 m to yield to the same moment of inertia as the micropiles. The bridge foundations' assigned loads were 300 kPa, which was equal to the soil foundations' weight-bearing capacity.

3.1 Stages of construction of Model 1 (without micropiles)

- Initial phase: Initial stresses generation using $K_0$ procedure before applying the bridge footing loads.
- Bridge loads: Activating the bridge foundations plate and applying the vertical stresses to the bridge foundations.
- Secant piles wall construction: Activating the plate element representing the secant piles as a shoring system before starting the excavation.
- Dewatering the soil between the underpass shoring walls up to −3.5 m.
- Excavating the soil between the underpass shoring walls up to −3.0 m.
- Dewatering the soil between the underpass shoring walls up to −10.5 m.
3.2 Stages of construction of Model 2 (with micropiles)

- Initial phase: Initial stresses generation using $K_0$ procedure before applying the bridge foundations loads.
- Bridge loads: Activating the bridge footing plate and applying the vertical stresses to the bridge foundations.
- Micropiles were constructed around the bridge foundations.
- Secant piles wall construction: Activating the plate element representing the secant piles as a shoring system before starting the excavation.
- Dewatering the soil between the underpass shoring walls up to −3.5 m.
- Excavating the soil between the underpass shoring walls up to −3.0 m.
- Dewatering the soil between the underpass shoring walls up to −10.5 m.
- Excavating the soil between the underpass shoring walls up to −10.0 m.

4. Analysis and results

The effect of constructing the micropiles around the existing bridge will affect the stress distribution underneath the bridge foundations and the foundations' settlement. Moreover, it will also affect the straining actions and deformations of the secant piles. The following section describes changes in soil stresses and deformations when constructing the micropiles. The changes in straining actions and deformations of the secant pile wall due to the construction of the micropiles have been illustrated. The straining actions and deformations of the micropiles have also been presented.

4.1 Effect on soil mass

Installing the micropiles all around the existing bridge foundations confines the soil underneath the bridge foundations, thereby decreasing the total and the lateral displacements.

For Model 1, without micropiles, Figure 8 shows the 3D colored contours of the soil mass and the bridge foundations. To clarify this, a vertical section along the bridge foundations transverse centreline is presented in Figure 8(b).

For Model 2, with micropiles, the 3D colored contours of the soil mass and the bridge foundations are presented in Figure 9(a). The vertical section along the bridge foundations transverse centreline is shown in Figure 9(b).

Figures 8 and 9 reveal that the maximum total displacement occurred underneath the bridge foundations centreline. It was 2.15 cm for Model 1 without constructing with micropiles and decreased to 1.135 cm for Model 2 when constructing with micropiles. So, installing micropiles all around the existing bridge foundations would decrease the bridge soil's settlement by approximately 47%.
Figure 8. Colored contours of the total displacement for Model 1 without micropiles: (a) 3D soil mass; and (b) vertical section along the transverse centreline of the bridge foundations.

Figure 9. Colored contours of the total displacement for Model 2 with micropiles. (a) 3D soil mass; and (b) vertical section along the transverse centreline of the bridge foundations.

Figure 10(a) and (b) shows the 3D colored contours of lateral displacement and the vertical section along with the bridge foundations transverse centreline, respectively, for Model 1 without micropiles, and Figure 11(a) and (b) shows them, respectively, for Model 2 with micropiles. Installing the micropiles all around the existing bridge foundations decreased the horizontal soil movement underneath the foundations' from 5.9 mm to 3.1 mm, also by approximately 47%.
Figure 10. Colored contours of the lateral displacement for Model 1 without micropiles: (a) 3D soil mass; and (b) vertical section along the transverse centreline of the bridge foundations

Figure 11. Colored contours of the lateral displacement for Model 2 with micropiles: (a) 3D soil mass; and (b) vertical section along the transverse centreline of the bridge foundations
Installing the micropiles all around the existing raft foundations' perimeter would reduce the additional stresses induced by the soil mass due to the loads on the existing foundations. The micropiles sustain a portion of these loads, as shown in Figures 12 and 13. Figures 12(a) and 13(a) show the 3D colored contours of the soil stresses for Models 1 and 2, respectively, and Figures 12(b) and 13(b) show the colored contours of the vertical section along the transverse centreline of the bridge foundations for Models 1 and 2, respectively.

**Figure 12.** Colored contours of the soil stress for Model 1 without micropiles: (a) 3D soil mass; and (b) vertical section along the transverse centreline of the bridge foundations.

**Figure 13.** Colored contours of the soil stress for Model 2 with micropiles: (a) 3D soil mass; and (b) vertical section along the transverse centreline of the bridge foundations.
4.2 Effect on existing bridge foundations

Excavating the soil and installing the side-support system for the underpass construction close to the existing bridge foundations would affect the latter. The bridge foundations' settlement due to the excavation of the side-support system is shown in Figure 14. Figure 14(a) shows that the foundations' maximum settlement would occur at the edge closest to the excavation and would be 2.15 cm. For Model 2, installing the micropiles all around the existing bridge foundations' perimeter would confine the soil underneath. The settlement of foundations would decrease to 1.135 cm, as shown in Figure 14(b). Besides, the maximum settlement would occur at the center of the bridge foundations, not on edge closest to the excavation. In other words, the micropiles would work as a barrier to reduce the effect of the excavation on the bridge foundations. The positive impact of constructing the micropiles around the existing building foundations' perimeter could also be noticed on the induced deformations and straining actions of the secant pile wall.

Figure 14. Colored contours of the bridge foundations settlement: (a) Model 1; and (b) Model 2.

4.3 Secant pile wall total displacement

A substantial decrease was observed for the total wall settlement, from 14 mm in Model 1 without micropiles (see Figure 15(a)) to 9.1 mm in Model 2 with micropiles (see Figure 15(b)).
4.4 Secant pile wall lateral displacement

The secant pile wall lateral deformations were decreased in the simulations using micropiles all around the perimeter of the existing bridge foundations. Figure 16(a) shows the lateral displacement of the secant pile wall for Model 1 without micropiles, and Figure 16(b) shows the lateral displacement of the secant pile wall for Model 2 with micropiles. The lateral wall displacement decreased from 4.4 mm in Model 1 without micropiles to 2.8 mm in Model 2 with micropiles, by 36%.

5. Conclusions

Constructing a new underpass along Al-Nasser Road in Riyadh close to the existing bridge foundations along Al-Haer Road will lead to an undesirable excessive settlement of the bridge foundations. To overcome this problem, it is proposed that micropiles be used along the perimeter of the existing bridge
foundations, which would work as a barrier to prevent the transfer of stresses and deformation along with the soil mass between the existing building and the side-support system of the new underpass.

In this study, two 3D numerical PLAXIS models were created to compare the sizes of the induced stresses and deformations in the two cases of not using micropiles (Model 1) and using micropiles (Model 2).

This study revealed that using micropiles all around the existing bridge foundations would have a dual benefit: it would decrease the settlement of the existing bridge foundations as a result of excavating the underpass and, simultaneously, it would decrease the induced straining actions and deformations of the side-support system needed for constructing the underpass due to loads on the existing bridge foundations.

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