Hindawi
Advances in Civil Engineering
Volume 2022, Article ID 2383781, 10 pages
https://doi.org/10.1155/2022/2383781

Research Article

Reinforcement of Concrete Shoring Systems by Prestressing

Hani Mekdash,[1] **Lina Jaber**,[1] **Yehya Temsah**,[1] **and Marwan Sadek**[2]

[1]*Beirut Arab University, (Civil and Environmental Engineering Department), Beirut, Lebanon*
[2]*Lebanese University, (Civil Engineering Department), Beirut, Lebanon*

Correspondence should be addressed to Hani Mekdash; hanimekdash@hotmail.com

Received 26 April 2022; Revised 2 August 2022; Accepted 26 August 2022; Published 23 September 2022

Academic Editor: Raizal Rashid

Reinforced concrete piles are useful structural elements to support deep excavations. A pile wall is usually supported by one or several rows of anchors, depending on the depth of the excavation and the nature of the soil retained. The purpose of this work is to investigate the efficacy of posttensioned piles in retaining a 10.0 m deep excavation without using tieback anchors. In addition to the conventional passive steel reinforcement, the piles in this system include steel strands placed eccentrically in their sections, and they are referred to as posttensioned piles. The performance of posttensioned piles is investigated using the finite element modeling software PLAXIS 2D. The results are experimentally validated on a large-scale construction site. The horizontal displacement of posttensioned piles in a 10 m deep excavation was found to be within allowable limits with a 7.36% difference in the horizontal displacement of pile top at the final excavation level in PLAXIS 2D. In terms of cost, PTP is executed at 35% cost less than the conventional reinforced method.

1. Introduction

Prestressed concrete technology is based on applying a compression force into the concrete by mechanically tensioning reinforcement strands, which introduces internal stresses that can counteract stresses produced from external loading. Comparing reinforced concrete beams of the same dimensions shows that prestressed beams can carry higher loads with smaller deflection than conventional reinforced concrete beams [1]. The deflection of piles is one of the main concerns in the design of shoring systems. Ground anchors or tieback anchors, nails, and struts are commonly used to support shoring systems laterally. Soil nails are shorter than ground anchors and are usually used to stabilize naturally existing slopes. Similar to ground anchors, struts provide lateral support for deep excavations with vertical structural retaining elements, such as soldier piles, contiguous piles, secant piles, or diaphragm walls; however, they make site accessibility difficult for construction work and machinery. Piles with tieback anchors have long been used to provide lateral support for deep excavations in the works of Broms [2], Huang et al. [3], and Gong et al. [4]. However, ground anchors often illegally trespass on neighboring properties, and they might sometimes get obstructed by infrastructure or underground facilities. In order to benefit from the effect of minimized deflection obtained due to the prestressing effect, the idea of posttensioned piles evolved. Posttensioned piles are piles that include prestressing strands in their sections in addition to reinforcing steel. After the piles are cast, the steel strands are tensioned using a hydraulic jack, creating compression forces in the pile that are able to counteract the tension forces due to soil pressure with less deflection than regular reinforced concrete piles (RCP). Soil mechanics textbooks suggest that cantilever pile walls should be used for excavations not exceeding the height of 4.5 m [5]. For deeper excavations, lateral support by means of tieback anchors is necessary. In this study, the horizontal displacement of PTP was compared to that of anchored RCP through an experimental study based on the work of Mekdash et al. [6]. Numerous studies have used FEM to predict the performance of structural steel and concrete elements [7] and [8]. In this study, the finite element software PLAXIS 2D is used to predict the displacement of PTP, which indicated satisfactory displacement values. Due to the minimized deflection observed in posttensioned piles (PTP), going further in-depth for excavations retained by

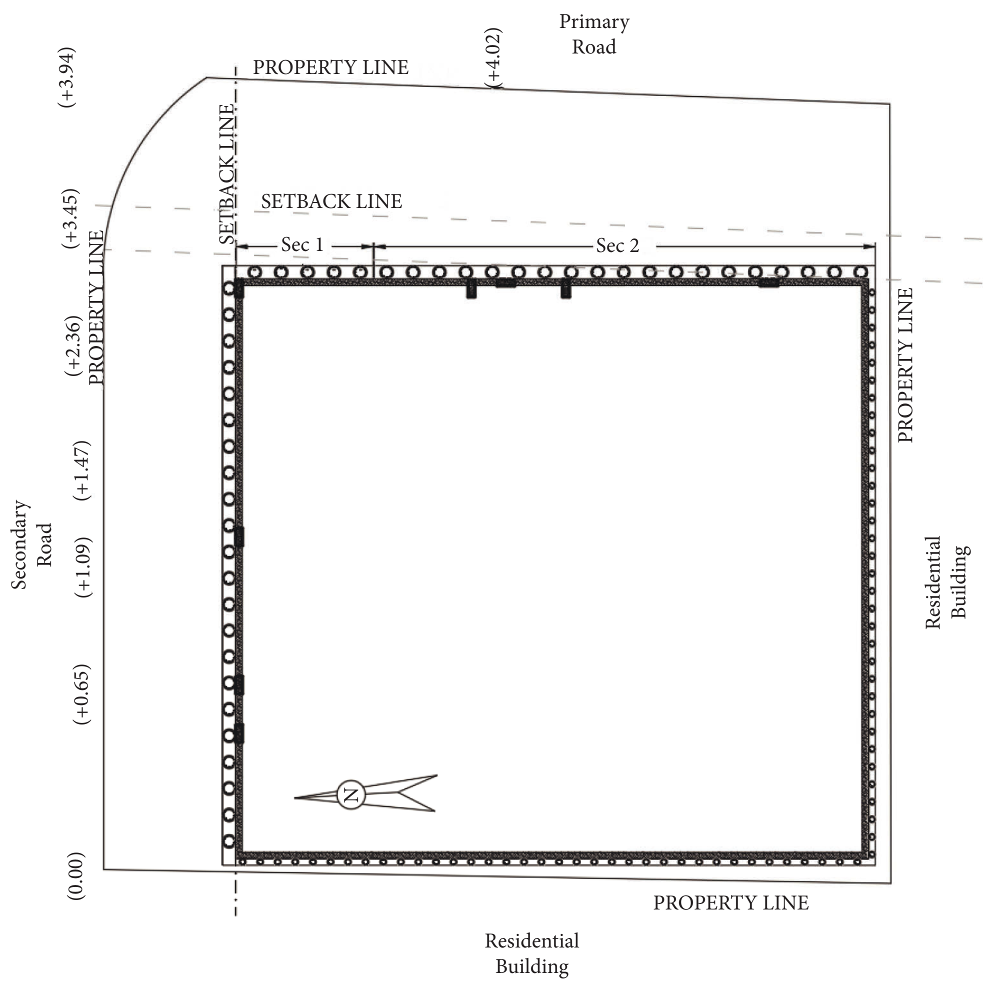

Figure 1: Site plan and surroundings.

posttensioned piles is now possible. Moreover, the tieback anchors can now be replaced by posttensioning strands added to the reinforced concrete pile section.

2. Materials and Methods

The purpose of this experiment is to study the effect of prestressing by using PTP to retain a deep excavation instead of using the conventional reinforced concrete piles (RCP) that are supported by tieback anchors. In order to achieve this, a large-scale experiment is performed on a construction site at the excavation stage. PTP was constructed on one stretch of the site and connected with a separate cap beam, whereas the rest of the piles on the construction site were typical reinforced concrete piles supported with tieback anchors. In this section, the experimental approach is explained in detail, including the soil and pile properties, in addition to the detailed construction steps.

2.1. Experimental Description. The lot on which the experiment was performed is a square site bounded by multistory buildings to the west and south, a main street to the east, and a secondary sloping road to the north (Figure 1). The purpose of this study is to design a safe shoring system without anchors. In order to achieve this, a set of anchored RC piles and PTP, without any lateral support, were cast in place on a construction site. A comparison between the two systems in terms of deflection was conducted using an inclinometer.

2.2. Soil Properties. The piles are retaining a three-layered soil (Figures 2 and 3) consisting of 6.0 m of poorly-graded SAND with silt (Layer 1) underlain by a 6.0 m layer of sandy lean clay to silty sand (Layer 2) underlain by a layer of SANDSTONE with SAND/silty SAND (Layer 3). Several laboratory tests were performed as per ASTM standards on samples selected from six investigatory boreholes, including wash sieve analysis, atterberg limits, moisture content, direct shear, unconfined compression tests, uniaxial compression for rocks, and point load index for rock fragments. The obtained soil properties of the three layers are represented in Table 1 as per the soil investigation report carried out for this project.

2.3. Piles. Retaining an excavation of 10.0 m, the shoring system designed for this project consists of 60 cm contiguous reinforced concrete piles (RCP), with a length of 15.0 m

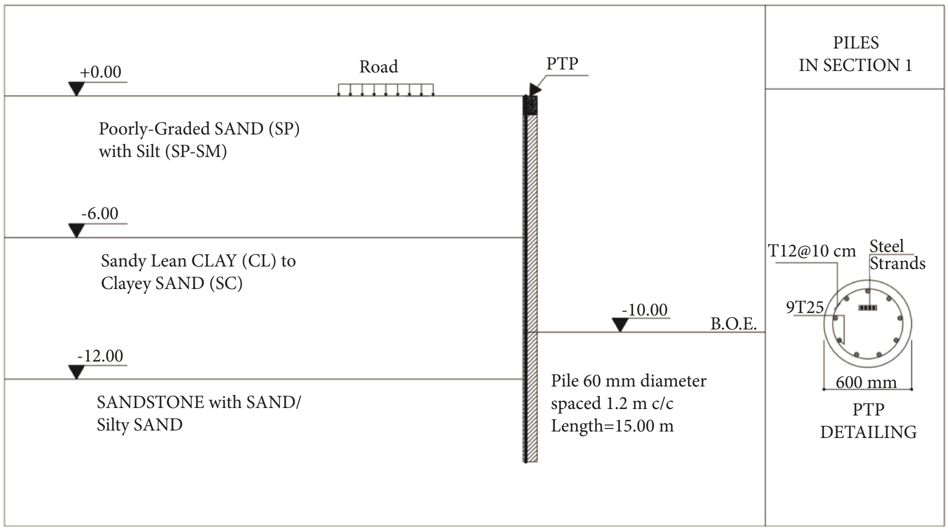

Figure 2: Shoring section 1.

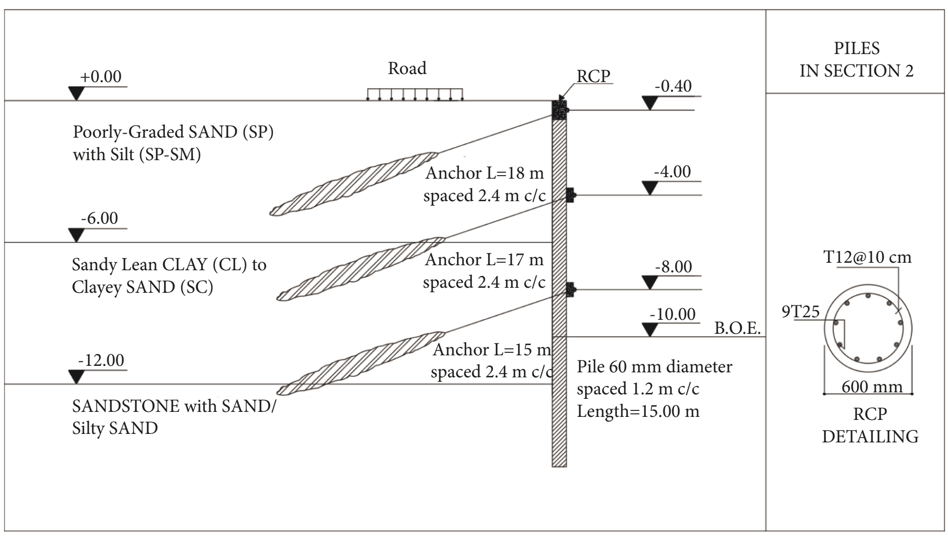

Figure 3: Shoring section 2.

Table 1: Mechanical properties of subsurface layers.

Property	Poorly graded sand with silt	Clayey sand	Sandstone
Bulk unit weight, γ (kN/m^3)	18.0	19.0	22.0
Drained angle of friction, ø (degrees)	36	22	40
Drained cohesion, c (kPa)	4	50	20
Poisson's ratio, γ	0.3	0.3	0.28
Undrained subgrade modulus coefficient, Ks (kN/m^3)	45000	45000	90000

spaced at 120 cm c-c. All piles are connected at the top with a cap beam of dimensions of 60×80 cm. The lateral support for this system is provided through multiple rows of tie-back anchors. Since the purpose of this study is to prove that prestressing techniques can be performed without using lateral supports, five posttensioned piles (PTP) were executed and connected with a separate cap beam on one stretch of the east side of the shoring system. The behavior of PTP was compared to that of the RCP by measuring the lateral deflection of both types using an inclinometer. Measurements were performed on two stretches of the same side of the excavation (Figure 1), designated as section 1 comprising PTP and section 2 comprising RCP, to ensure that the same soil properties and loading conditions are applied to both sections.

The shoring system was designed for RCP and PTP with material properties described in Table 2. Both types of piles were constructed using the cast in the drilled hole method

Table 2: Properties of raw material.

Material	Properties
Concrete for RCP	f'c = 30 MPa, $\mu = 0.16$, and $E = 25.7$ GPa
Concrete for PTP	f'c = 35 MPa, $\mu = 0.16$, and $E = 27.8$ GPa
Steel bars	T25 Grade 60 fy = 420 MPa, $d = 25$ mm, $A = 510\ \text{mm}^2$, and Es = 195 kN/m^2
Steel strands	$d = 15.24$ mm 7 wire strands grade 270 k, fy = 1860 MPa, Aps = 140 mm^2, and Es = 195 kN/m^2

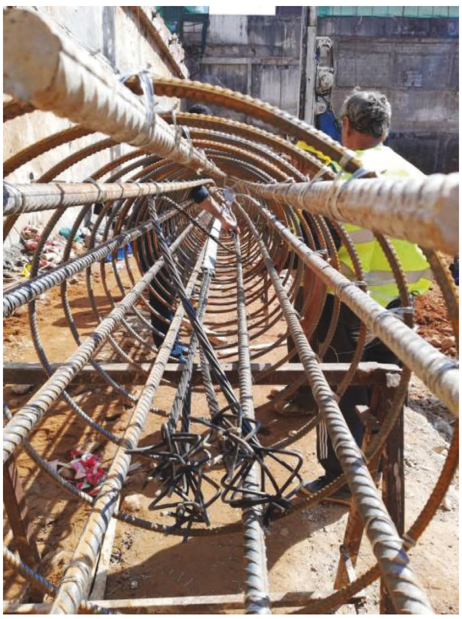

Figure 4: Steel cages with bulb-shaped strands.

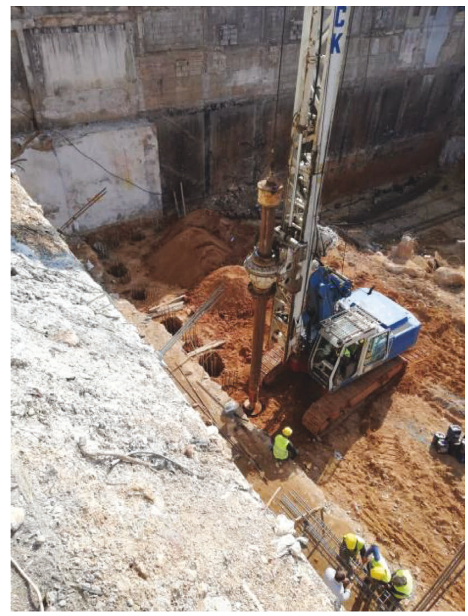

Figure 5: Pile hole drilling.

with the same length, embedment depth, and reinforcing steel, and they were both retaining the excavation under the same loading conditions. However, the steel reinforcement cage in the PTP had additional prestressing strands located in the tension zone and stressed prior to excavation works (Figure 2). As for the RCP, three rows of anchors were executed to support the retaining pile wall (Figure 3), based on an analysis done to ensure that the lateral displacement will remain less than admissible values. The justification of a shoring system toward the service limit states is based on verifying that the displacement of the shoring wall is less than the allowable fixed values. These limit values are usually established before the start of the project by structural/geotechnical experts, taking into account the angular distortion tolerances and displacement of a shoring wall and the structures in the influence area of the work NF P 94–282. The limit values should be estimated based on comparable experience and the recognition of neighboring structures. The sensitivity of neighboring structures also must be taken into consideration. Accordingly, in this project, the maximum allowable pile displacement for this project is considered 0.3% of the height of the excavation.

2.4. Experimental Procedure. The steel reinforcement cages for both RCP and PTP were prepared on-site (Figure 4) using 9T25 vertical reinforcement and T10@150 mm spiral reinforcement based on results from FEM software PLAXIS 2D. The prestressing system adopted in this experiment is the posttensioned bonded system, with one dead end at the bottom of the pile. In order to achieve a firmly fixed end, the steel strands were bent to form a bulb shape. Four 7-wire steel strands were inserted in a 70×25 mm flat duct where a bonded length of 1.5 m was maintained. The prestressing strands were added to the tension zone with an eccentricity of 20 cm. Metal tubes with a square hollow section 15.0 m long made of $50 \times 50 \times 3$ mm profiles were welded to the piles' steel cages to take inclinometer readings. Pile holes are drilled (Figure 5) for both PTP and RCP. The steel cages for both PTP and RCP are lowered in the drilled holes with additional prestressing strands for PTP. The PTPs were connected at the top with a capping beam of 6 m in span, which was also cast with ready mix concrete. It is important to note that the cap beam of the RCP was not connected to that of the PTP to make sure that each system is functioning separately. Each strand was tensioned in PTP with a force of 20 tons using a hydraulic jack (Figure 6) with an average elongation of 7 mm. The ducts were then filled with a grout of a water-cement ratio of 0.45, and the PTPs were marked in yellow for identification (Figure 7). The lateral deflection values were recorded at three excavation levels, at the ground surface (0 m bgs), at the mid of excavation (5 m bgs), and at the bottom of excavation (10 m bgs).

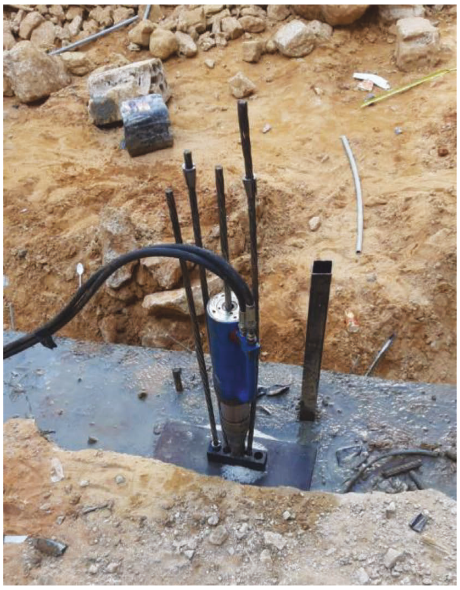

Figure 6: Strand tensioning.

Figure 7: PTP in section 1.

2.5. Data Collection. Horizontal displacements of piles were measured using an inclinometer system. The system consists of an inclinometer probe, a dummy probe, an inclinometer cable, and a data logger (Figure 8). The inclinometer probe, which is equipped with measuring, is lowered into the exploration hole. The readings are recorded by the data logger at regular intervals of 0.5 m. The displacement is measured based on the inclination angle of the inclinometer probe from a vertical direction. Each measurement cycle starts with the initial zero measurements, and it should be performed directly after preparing the exploration hole. Then, successive measurements are carried out at time intervals depending on the construction work progress.

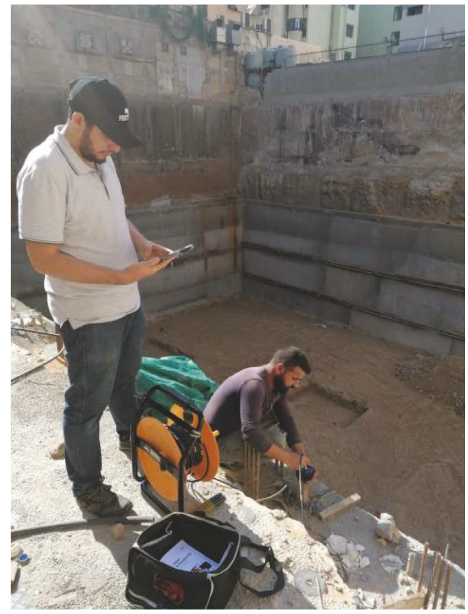

Figure 8: Taking inclinometer readings on-site.

The deflection results for PTP and RCP are recorded and illustrated in Figure 9. Inclinometer readings were taken for PTP before and after prestressing; however, cambering effects could not be noticed before excavating works, as the pile was totally embedded in the soil. At the mid-level of excavation (5 m bgs), the displacement at the top of the PT pile was recorded as 7 mm, whereas it was 2 mm at the top of the RC pile. At the bottom of the excavation (10 m bgs), the displacement at the top of the PTP reached 15.5 mm, whereas for the RC pile it was 2.5 mm.

3. Numerical Modeling

Numerical modeling of the excavation retained by PTP was carried out using PLAXIS 2D V20. Modeling of elastic and elastoplastic materials is explained in this section.

3.1. Modeling of Soil in PLAXIS 2D. Determining the dimensions of the model is a critical step in the numerical simulation of finite element models. In order to decrease the effect of boundary conditions on the predicted ground movements, Briaud and Lim [9] recommendations were applied where the depth of soil below the bottom of excavation D should be around two to three times the depth of the excavation H, ($D = 3 \times$ H), while the width B is the sum of H and D, ($B = H +$ D). The ideal model boundaries that do not affect the analysis results are presented in Figure 10.

The density of the finite element mesh plays an important role in the numerical simulation of any structure. PLAXIS 2D allows the user to choose a mesh density ranging from very coarse to fine. The mesh generation in Plaxis is fully automatic and based on a robust triangulation procedure. The user can choose between 6-noded or 15-noded elements. In this study, 15-noded triangular elements are considered for higher accuracy and an enhanced ability to

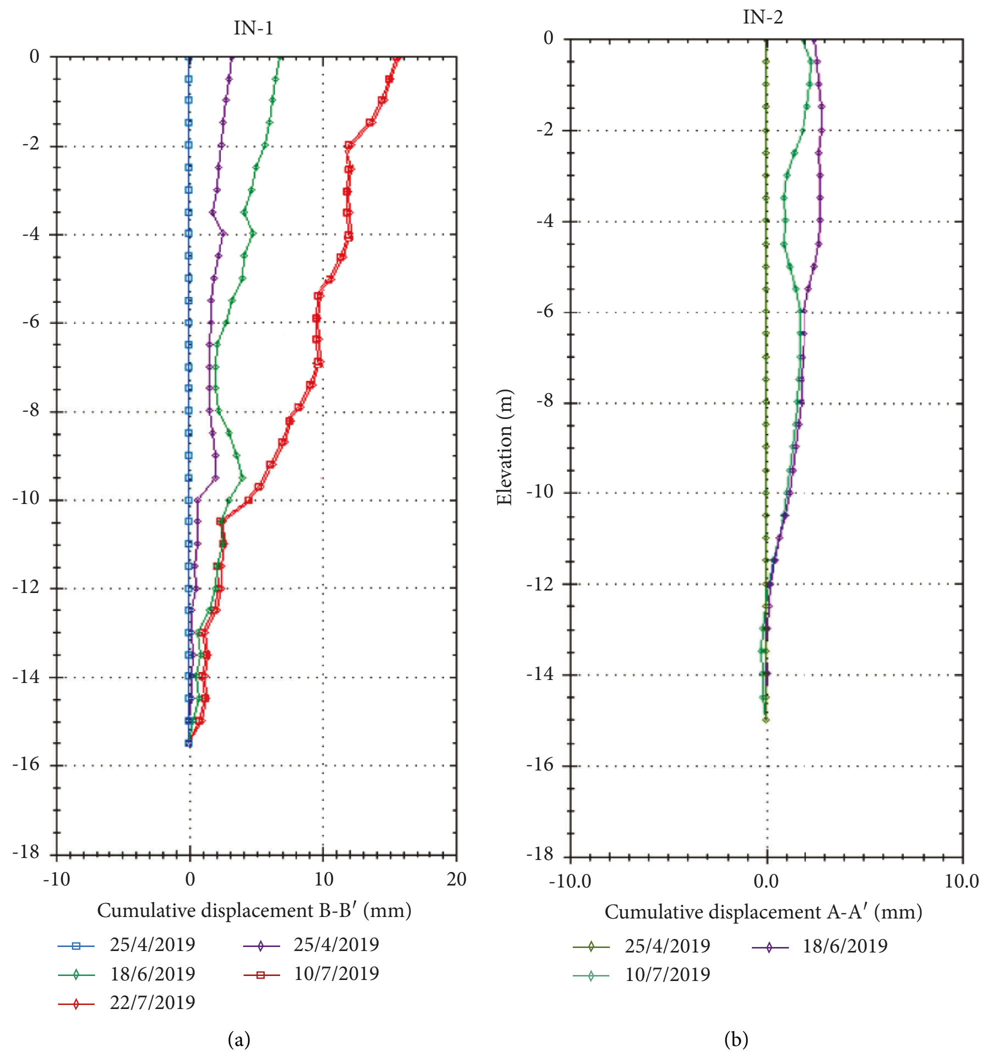

Figure 9: Inclinometer reading plot for (a) PTP and (b) RCP.

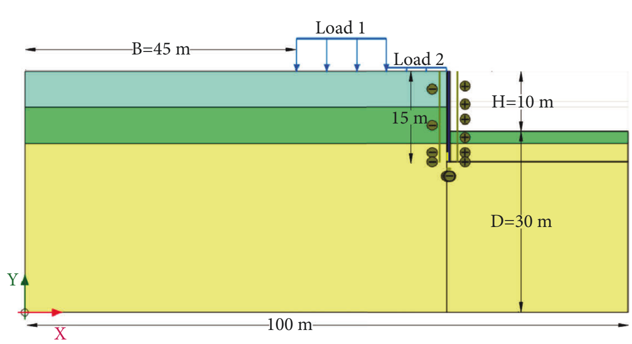

Figure 10: PLAXIS 2D V20 model.

capture stress concentrations. It is also important to perform several trials where the global factor of safety maintains similar trends if the mesh is to be refined in the vicinity of the targeted structures of the model. In this study, several trials were performed to determine the suitable mesh size, which maintains a similar trend of the horizontal displacement of piles (Table 3); the mesh was chosen to be medium except around the PTP cluster, and it was chosen as fine. The number of soil elements is 1998 and the average element size (AES) is 1.703.

Table 3: Effect of change in mesh size on the horizontal displacement of PTP.

Horizontal displacement of pile (cm)	Mesh size
2.226	Very coarse
2.227	Coarse
2.228	Medium
2.228	Fine
2.228	Very fine

The soil behavior was simulated using the Hardening Soil Model with Small Strain Stiffness (HS small model), as it has been proven the most adequate in simulating excavations. It accounts for most of the soil behavior features; it differentiates between loading and unloading soil stiffness, develops irreversible strains by reaching a yield criterion,

Table 4: Mechanical properties of of elastic and elastoplastic soil used for the HS small model.

Property	Poorly graded sand with silt	Clayey sand	Sandstone
Triaxial compression stiffness, E_{50}^{ref} (MPa)	50	80	100
Primary oedometer stiffness, E_{oed}^{ref} (MPa)	50	80	100
Unloading/reloading stiffness, E_{ur}^{ref} (Mpa)	150	240	300
Poisson's ratio, ν_{ur}	0.2	0.2	0.2
Small strain stiffness, G_0^{ref} (MPa)	50	56	72
Shear strain at $0.7G_{0,}\gamma_{0.7}$	1.5×10^{-4}	1.32×10^{-4}	1.03×10^{-4}

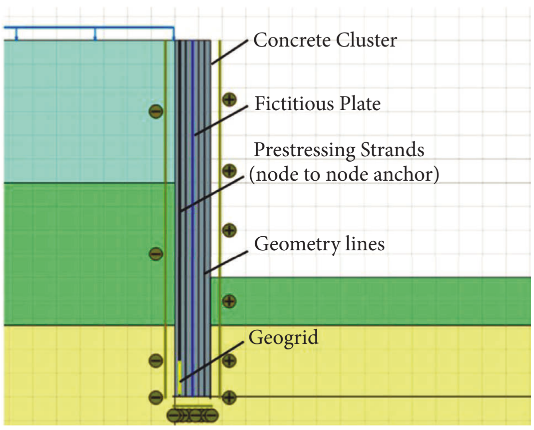

Figure 11: Modeling of prestressed concrete piles in PLAXIS 2D.

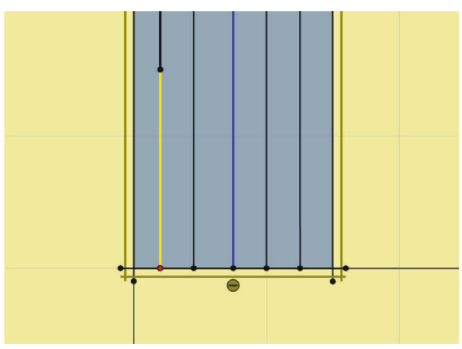

Figure 12: Interface extended beyond the boundaries of the pile cluster.

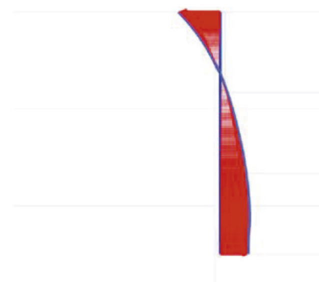

Figure 13: Horizontal displacement of pile head after prestressing (cambering effect).

Figure 14: Horizontal displacement of pile head at final excavation level.

and provides a nonlinear elastic stress-strain relationship at small strains [10]. The properties of the HS small model are listed in Table 4.

Two uniform loads were applied to the topsoil. Load 1 = 50 kPa corresponding to the load of the primary road adjacent to the test piles and Load 2 = 20 kPa representing the load expected in the setback limit extending from the test piles to the primary road.

3.2. Modeling of Piles in Plaxis 2D. In order to model the PTP, a concrete cluster with the same elastic properties as the actual PTP on-site and dimensions pertaining to this pile in nonporous condition were defined. For the sake of monitoring the deformation and the structural forces developed in the pile cluster, a fictitious plate element of very low bending stiffness with less weight was defined at the centerline of the cluster (Figures 11 and 12). To add a prestressing force to the pile, a node-to-node anchor was employed to simulate the steel strands, and it was eccentrically placed at 20 cm from the centerline of the cluster (Figures 11 and 12). To simulate the proper interaction between the pile and the soil surrounding it, interface elements were defined along the pile height while taking into consideration the soil retained. In order to omit stress oscillations at the corners of the stiff pile cluster and to avoid the generation of inflexible points at its corners, which may cause bad stress results, the interface was slightly extended (1-2 mm) beyond the boundaries of the cluster as shown in Figure 12.

4. Results and Discussion

4.1. Numerical Modeling Outcomes and Discussion. PTP results were monitored at two stages: prior to excavation (at 0 m bgs) and at the final excavation level (at 10 m bgs). Before excavating the soil and just after prestressing, the

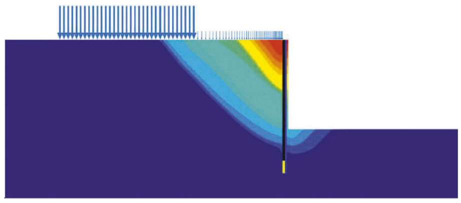

FIGURE 15: PLAXIS output global stability.

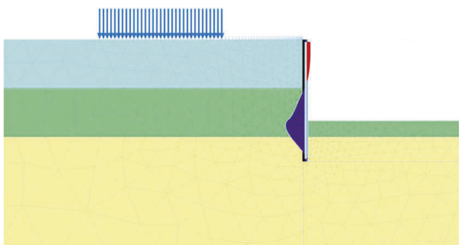

FIGURE 16: Bending moment diagram for PTP.

results in Figure 13 show the pile cambering effect due to prestressing. The pile head's horizontal displacement at the final level of excavation is 2.23 cm (Figure 14). At the final level of excavation, the global factor of safety is 1.691 > 1.5 (Figure 15). Figure 16 shows the bending moment diagram of PTP where the maximum bending moment $M = 292.32$ kN·m. Noting that the length of the pile is $L = 15$ m and considering the ground surface as the zero level ($y = 0$), the location of the maximum bending moment was determined from Figure 16, and it is found to be at $y = -10.562$ m. For two different excavation stages, the stress distribution in the pile section at the location of the maximum moment is shown in Figures 17 and 18. Figure 17 shows that the pile section at $y = -10.562$ m is in compression with a maximum value of 907.8 kN/m^2 to the side of the retained soil and a minimum value of 483.2 kN/m^2 to the side of the excavation. Figure 18 shows that the pile section at $y = -10.562$ m is in tension to the side of the retained soil with a value of 3123 kN/m^2 and in compression to the side of the excavation with a value of 5029 kN/m^2. It is evident that the values obtained for both stages are less than the maximum allowable stresses in prestressed concrete, where the maximum allowable tension stress is 3200 kPa and the maximum allowable compression stress is 43000 kPa (BS EN 1992-1-1:2004) [11].

4.2. Comparison between Experimental and Numerical Approaches. Since the pile is embedded in rock, it is expected to be partially fixed at the bottom. Accordingly, the relative horizontal displacement of PTP on the plaxis is compared to that of PTP on-site, which was measured using an inclinometer (Figure 9). Experimental and numerical values of the horizontal displacement of PTP are plotted in Figure 19. Both curves show similar displacement trends, and the horizontal displacement at the top of piles at the final excavation level was 15.5 mm for PTP on site and 14.4 mm for PTP in PLAXIS (Figure 14), indicating a 7.36% difference between actual and numerical readings.

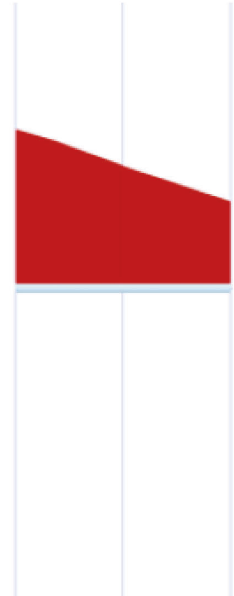

FIGURE 17: Normal stress distribution at $y = -10.562$ m after prestressing.

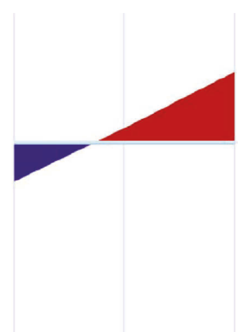

FIGURE 18: Normal stress distribution at $y = -10.562$ m at final excavation level.

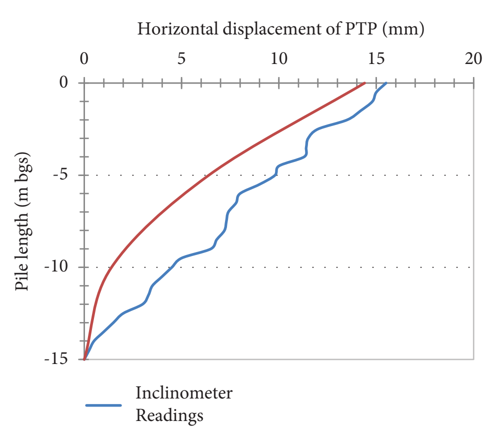

FIGURE 19: Relative displacement versus inclinometer displacement values of PTP.

4.3. Analysis and Discussion. The prestressing force developed in the pile produced cambering effects in the concrete section, which reduced the displacement of PTP on the site when no lateral supports were used. Typically, the prestressing force plays an important role in increasing the section's axial capacity and assuring full inertia where the pile, which is acting as a long cantilever, and could horizontally deviate within an acceptable range without the use of lateral supports.

4.4. Cost Analysis. For practical engineering, the PTP technique turns out to be economical compared to the RCP in terms of raw materials, workmanship costs, and time of execution. The following prices were considered. The cost of the RC pile, including workmanship and raw material considering properties in Table 4, is 170\$/m, whereas the cost of the PTP pile including workmanship and considering properties in Table 2 is 110\$/m. The cost of anchors, including material as per Table 2 and workmanship, is 50\$/m. The cost was calculated at $\$/m^2$ of shoring wall. As per the cost comparison table, it is evident that a reduction of 35% in cost is expected when the PTP system is adopted in excavations of 10.0 m in height with soil conditions similar to those prevailing in this study.

5. Conclusion and Recommendations

Ground anchors have long been used to provide lateral support for shoring systems in deep excavations. However, the use of such anchors is hindered due to property limitations or due to the existence of subsurface obstacles. This study suggests applying prestressing effects to piles without using lateral support. This method is investigated experimentally and numerically based on the criteria of horizontal displacement.

In a deep excavation project, posttensioned piles (PTP) and piles retained with ground anchors (RCP) were both executed and monitored for horizontal displacement using an inclinometer and the findings as follows:

(i) The horizontal displacement of both PTP and RCP was found to be within allowable limits.
(ii) The stresses developed in the cross section of PTP were also found to be less than the allowable.
(iii) The horizontal displacement of PTP on-site showed similar behavior in PLAXIS 2D with a 7.36% difference in the horizontal displacement of the pile top at the bottom of the excavation level.
(iv) PTP is less by 35% than RCP in terms of cost. It is executed with less material, workmanship, and time.
(v) The PTP was proven to be able to retain the 10.0 m excavation with no lateral supports or tiebacks with the aid of the prestressing effect applied at the top of the pile while exhibiting horizontal displacement of acceptable value.

Finally, it is important to note that the results obtained in this study are limited to this experiment for the existing soil conditions, the depth of excavation, and material properties. In fact, it is advised that this study is further investigated by analyzing the performance of PTP in deeper excavations using other geometrical configurations, different types of soil, and additional arrangements/configurations of prestressed concrete piles in order to widen the field of recommendations.

Data Availability

The data supporting the results are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Hani Mekdash conceived of the presented idea, carried out the experiment, performed the numerical analyses, and wrote the manuscript. Dr. Lina Jaber, Dr. Yehya Temsah, and Dr. Marwan Sadek all provided critical feedback, supervised the experimental work, reviewed, and edited the manuscript.

References

[1] M. Vaško, M. Handrik, M. Rác et al., "The damage analysis of the reinforced concrete beam and the prestressed reinforced concrete beam," *MATEC Web of Conferences*, vol. 157, Article ID 02055, 2018.

[2] B. Broms, "Design and construction of anchored and strutted sheet pile walls in soft clay," *Second International Conference on Case Histories in Geotechnical Engineering*, vol. 3, pp. 1515–1550, 1988.

[3] C. Huang, W. Z. Ren, and L. W. Kong, "New mathematical modelling of stabilizing pile with prestressed tieback anchors," *Mathematical Problems in Engineering*, vol. 2013, Article ID 601508, 12 pages, 2013.

[4] W. Gong, H. Huang, C. H. Juang, and L. Wang, "Simplified-robust geotechnical design of soldier pile–anchor tieback shoring system for deep excavation," *Marine Georesources & Geotechnology*, vol. 35, no. 2, pp. 157–169, 2015.

[5] M. Long, C. Brangan, C. Menkiti, M. Looby, and P. Casey, "Retaining walls in dublin boulder clay, Ireland," *Proceedings of the Institution of Civil Engineers - Geotechnical Engineering*, vol. 165, no. 4, pp. 247–266, 2012.

[6] H. Mekdash, L. Jaber, and Y. Temsah, "Cantilever shoring piles with prestressing strands: an experimental approach," *World Academy of Science, Engineering and Technology International Journal of Structural and Construction Engineering*, vol. 15, no. 6, 2021.

[7] M. S. Es-Haghi, A. Shishegaran, T. Rabczuk, and T. Rabczuk, "Evaluation of a novel Asymmetric Genetic Algorithm to optimize the structural design of 3D regular and irregular steel frames," *Frontiers of Structural and Civil Engineering*, vol. 14, no. 5, pp. 1110–1130, 2020.

[8] M. A. Naghsh, A. Shishegaran, B. Karami et al., "An innovative model for predicting the displacement and rotation of column-tree moment connection under fire," *Frontiers of Structural and Civil Engineering*, vol. 15, no. 1, pp. 194–212, 2021.

[9] J. L. Briaud and Y. Lim, “Soil nailed wall under piled bridge abutment: simulation and guidelines,” *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 123, no. 11, pp. 1043–1050, 1997.

[10] R. F. Obrzud and A. Truty, *The hardening soil model- A practical guidebook*, Elmepress International, Port Washington, New York, USA, 2018.

[11] British Standards Institution, *Eurocode 7: Part 1, General Rules (Together with United Kingdom National Application Document)*, British Standards Institution, London, 1995.