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Cantilever Shoring Piles with Prestressing Strands: An Experimental Approach

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Abstract**—**Underground space is becoming a necessity nowadays, especially in highly congested urban areas. Retaining underground excavations using shoring systems is essential in order to protect adjoining structures from potential damage or collapse. Reinforced Concrete Piles (RCP) supported by multiple rows of tie-back anchors are commonly used type of shoring systems in deep excavations. However, executing anchors can sometimes be challenging because they might illegally trespass neighboring properties or get obstructed by infrastructure and other underground facilities. A technique is proposed in this paper, and it involves the addition of eccentric high-strength steel strands to the RCP section through ducts without providing the pile with lateral supports. The strands are then vertically stressed externally on the pile cap using a hydraulic jack, creating a compressive strengthening force in the concrete section. An experimental study about the behavior of the shoring wall by pre-stressed piles is presented during the execution of an open excavation in an urban area (Beirut city) followed by numerical analysis using finite element software. Based on the experimental results, this technique is proven to be cost-effective and provides flexible and sustainable construction of shoring works.

Keywords**—**Excavation, inclinometer, prestressing, shoring system.

I. INTRODUCTION

SINCE urban areas are becoming highly congested, underground space is becoming a necessity. Nevertheless, excavating next to structures and roads is critical especially when excavations are deep. The design of a shoring system is tailor made for every project based on soil properties and adjacent structures. In most cases, tie back anchors or struts are needed in order to support the shoring system laterally. Piles with tie back anchors have been traditionally used to retain deep excavations. Broms investigated several methods to increase the stability of anchored and strutted sheet pile walls in soft clay [1]. Huang et al. proposed new differential equations for analyzing the stability of stabilizing piles and validated them using FEM [2]. Gong et al. proposed a simplified robust geotechnical design method to account for the uncertainties in the design parameters of shoring systems retained with tie back anchors [3]. However, tie back anchors are not always executable, as they might trespass neighboring structures illegally and they are sometimes restricted because of underground facilities. Accordingly, cantilever piles can be a possible alternative with emphasis on the horizontal displacement at top of piles. The justification of a shoring system towards the service limit states includes verifying that the displacement of a shoring wall is less than allowable fixed values. Nevertheless, determining the allowable displacement for a project is challenging since information in the literature on this issue are limited. However, numerous research efforts have been made to compile data from real case histories on the maximum displacement of retaining systems in order to provide basis for displacement estimation. Peck gathered information from deep excavations around the world on the maximum horizontal displacement of supporting walls [4]. The values were sorted according to the type of supported soil and they were divided by the depth of excavations which provided basis for engineers to estimate the maximum horizontal displacement for different types of soils. Similarly, and based on experience gained from previously documented performance of retaining walls in deep excavations NAVFAC DM-7 [5] indicated that walls might laterally displace by an amount of 0.5% the height of excavation H in stiff clays. On the other hand, walls in sands and silts might displace by a value of 0.2% H. Along the same lines, Long et al. analyzed 36 deep excavation cases in the literature divided between propped and anchored in clayey soil and realized that the values of maximum horizontal displacement did not exceed 0.3% of the height of the excavation in cantilever walls [6]. In a further work, Long et al. reported a case of a successful cantilever wall sustaining a 7.5 m excavation in Dublin boulder clay adjacent to a road [7]. The cantilever pile wall consisted of 60 cm contiguous piles spaced at 75 cm c-c and inclinometer measurements at final excavation level did not exceed 13 mm when the maximum allowable displacement decided for the project was 25 mm to avoid damaging the adjacent road. Consequently, this case encouraged engineers later to construct cantilever walls sustaining 8.0 m excavations in Dublin clay.

Although the literature includes information that helps in determining the potential lateral displacement in shoring systems, explicit allowable displacement limits remain insufficient and they are usually qualitative and not quantitative. In fact, most soil mechanics text books suggest that cantilever walls can be used to sustain excavations not exceeding a height of 4.5 m [8]. Contrarily, some engineers rely on rules of thumb to determine the maximum horizontal displacement which might sometimes be in the order of 0.5% the height of the excavation [9]. Considering the fact that displacement limits of a shoring system are usually controlled by the allowable displacement of the adjacent structures, the

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responsibility in every project is typically put on the geotechnical engineer to determine the maximum allowable displacement taking into account the displacement and angular distortion tolerances of the shoring wall and of the structures carried, associated or established in the area of influence of the works.

In order to minimize the displacement of cantilever shoring piles, the concept of prestressing is proposed and applied in this study. Prestressing technique is mostly used in reinforced concrete slabs or beams in order to increase their effective stiffness leading to reduction in their deflections. The same concept is applied in this study; however, it is used in reinforced concrete shoring piles. Aiming to apply the concept of prestressing in shoring piles, prestressing strands were added to some piles of a shoring system retaining a deep excavation. The piles were post-tensioned and monitored during and after excavation works. The studied piles were not supported laterally; they were only embedded in soil which makes them behave as cantilever piles. Based on the literature above, on past local experience and taking into consideration the importance and quality of the structures proximate to the excavation. The maximum accepted horizontal displacement value adopted in this study to protect the adjacent structures is considered to be in the order of 0.3% H which is 30mm.

II. Site and Experimental Description

The experiment is performed on a shoring system designed for a project comprising a multi-level commercial and office building with three basements. The bottom of excavation is anticipated at 10.0 m below ground level. The site has a nearly square shaped plan (Fig. 1). Two different shoring systems were designed for this project. The first system included typical reinforced concrete contiguous piles supported by multiple rows of tie back anchors. The second system included cantilever piles with prestressing strands added to their section eccentrically and tensioned after concrete pouring without using tie back anchors.

Both systems were performed in the same excavation. RCP with tie back anchors were performed on all sides of the excavation except for one stretch referred to as section 1 (Fig. 1) where cantilever piles were executed. In order to make sure that both systems function independently, the cantilever piles were tied with a separate pile cap. Monitoring was carried out in section 1 and section 2 of the project using an inclinometer.

The soil properties of the site were determined prior to excavation works by a geotechnical consultancy firm. The properties are provided in Table I as retrieved from the geotechnical investigation report. Based on the data in this table, the design of both shoring systems was performed.

Layer 1 has a thickness of 6.0 m and it consists of SAND with Silt. Layer 2 has a thickness of 6.0 m also and it consists of sandy lean CLAY to Clayey SAND. Layer 3 lies directly beneath layer 2 and it consists of SANDSTONE with SAND/ silty SAND with clayey SAND infillings.

Based on the soil properties and surrounding structures, the shoring system designed for this project included 60 cm RCP 15.0 m long spaced at 120 cm c-c connected with a cap beam at top. The embedment depth needed for the piles was 5.0 m. 9T25 were required for vertical reinforcement and T10@150mm for spiral reinforcement. Three rows of tie back anchors were necessary to support the system laterally. This system was applied for all the sides of the excavation except for section 1 where no tie back anchors were drilled. The piles in section 1 had the same vertical and spiral reinforcement as all the piles around the sides of the excavation with 4 prestressing strands added to the pile section.

The properties of raw material used in construction are summarized in Table II.

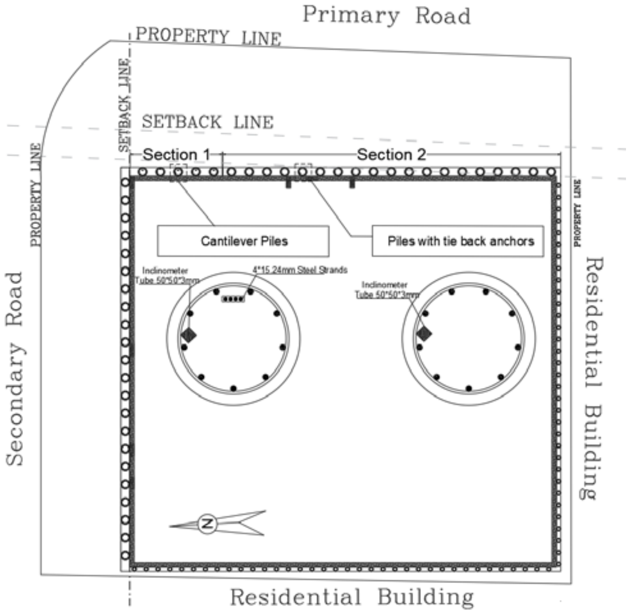

Fig. 1 Site Layout

TABLE I
GEOTECHNICAL PARAMETERS OF SUBSURFACE LAYERS

Property	Layer1	Layer2	Layer3
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
Undrained Young Modulus, E (kPa)	50000	80000	100000
Poisson’s ratio, μ	0.3	0.3	0.28
Undrained Subgrade Modulus Coefficient, Ks (kN/m^3)	45000	45000	90000
Coefficient of Lateral Earth Pressure at Rest, K_0	0.41	0.63	0.36
Coefficient of Lateral Active Earth Pressure, K_a	0.23	0.45	0.22
Coefficient of Lateral Passive Earth Pressure, K_p	3.85	2.20	4.60

TABLE II
PROPERTIES OF RAW MATERIAL

Material	Properties
Concrete for RCP	f’c = 30 MPa, μ = 0.16, E = 25.7 GPa
Concrete for PTP	f’c = 35 MPa, μ = 0.16, E = 27.8 GPa
Steel Bars	T25 Grade 60 fy = 420 MPa, d = 25 mm, A = 510 mm^2, Es = 195 kN/mm^2
Steel Strands	d = 15.24 mm 7wire strands Grade 270k, fy = 1860 MPa, Aps = 140 mm^2, Es = 195 kN/mm^2

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III. CONSTRUCTION AND EXPERIMENTAL PROCEDURE

A. Construction Works

Steel cages of 9T25 vertical reinforcement and T10@15mm spiral reinforcement were prepared for all piles in this project (Fig. 2). For piles in section 1 only, four steel strands of 7 wires each were inserted in a 70×25 mm flat duct and positioned next to the reinforcing steel in the tension zone with an eccentricity of 20 cm from the center of the pile to the side of the retained soil (Fig. 4). Since the strands are to be tensioned afterwards (post-tensioned), a bonded length of 1.5 m was maintained at the bottom of the pile and the strands were bulb shaped for a better fixation in concrete (Fig. 2). For piles in sections 1 and 2 only, inclinometer monitoring tubes of dimensions 50×50×3mm were also added to the steel reinforcement cage.

Fig. 2 Steel reinforcement structure

Pile holes were drilled using a drilling rig into a depth of 15.0 m (Fig. 3). The structure of reinforcing steel bars was directly lowered into the drilled holes. Ready mix concrete was then poured in the holes containing the reinforcement structures. The piles were tied with a cap beam at top of dimensions 1000×600 mm. The cap beam for piles in section 1 was not connected to the cap beam tying the rest of the piles in this project and it was also cast using ready mix concrete.

Fig. 3 Pile holes drilled to a depth of 15.0 m

In section 1, every steel strand was tensioned solely using a hydraulic jack (Fig. 5) by a force of 20 tons and the ducts were then filled with grout. Excavation was then performed in three stages. Tie back anchors were performed at the end of every stage on all sides of the excavation except for section 1. The anchors were of length 18 m, 17 m and 15 m for rows 1, 2 and 3 respectively and they were spaced at 2.4 m c-c.

Fig. 4 Piles in Section 1 with prestressing strands added to the conventional reinforcement structure

Fig. 5 Tensioning strands using a Mono jack

B. Displacement Monitoring

Inclinometer monitoring tubes were added into the reinforcement structure in sections 1 and 2. Inclinometer measurements were taken at three levels: at ground surface, at midway of excavation and at the bottom of excavation. The inclinometer probe which is equipped with a measuring is lowered into the exploratory tube. The measuring is connected to a data logger which records displacement readings. The inclinometer reads the inclination angle of the inclinometer probe from vertical direction. Each cycle starts from the initial zero measurement and then successive measurements are carried out at targeted construction stages.

IV. ANALYSIS AND DISCUSSION

The inclinometer readings taken on site indicate the horizontal displacement along the pile length in sections 1 and 2. The displacement of piles at top is very critical in shoring systems since the piles at this location are not supported. The maximum displacement of piles in a shoring system occurs when the final excavation level is reached. The inclinometer readings taken on site were recorded by the data reading console equipped with the inclinometer and they were summarized in Fig. 7.

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Fig. 6 Taking inclinometer readings at final excavation level

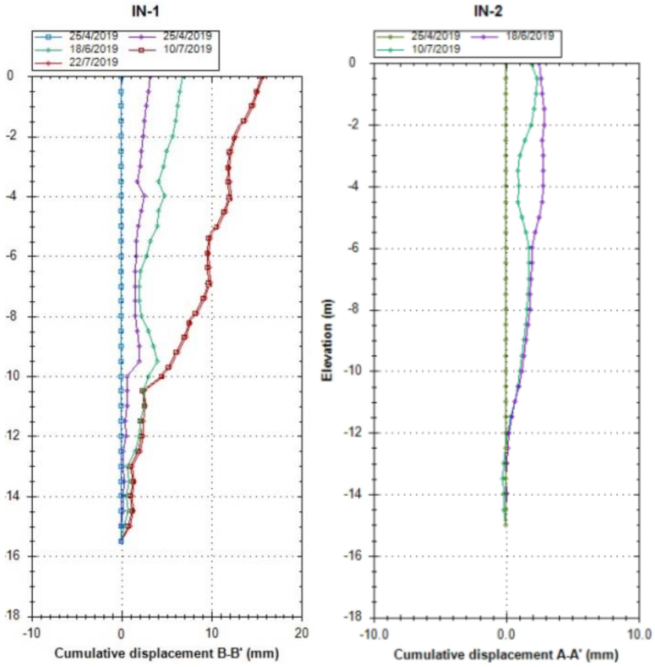

Fig. 7 Inclinometer readings at different construction stages

Inclinometer 1 IN-1 was measuring the horizontal displacement in section 1 where cantilever piles were executed whereas IN-2 was measuring the displacement in section 2 where piles were supported laterally using tie back anchors. Inclinometer readings were recorded before excavation works proceeded, at mid of excavation and at final level of excavation. For piles in section 1 only, inclinometer readings were also taken directly after strands were tensioned and 12 days after the final excavation level was reached. Before excavation works proceeded, the piles showed no displacement. At mid-level of the excavation, the horizontal displacement of piles in charts IN-1 and IN-2 began to increase until it reached its maximum at final excavation level.

The inclinometer readings prior to excavation works were zero and this was to indicate the reference of the following readings. At mid-level of excavation, the piles in section 1 exhibited a displacement value of 7 mm whereas the piles in section 2 exhibited a displacement of 2 mm. At final level of excavation, the displacement value of piles in section 1 reached 15.5 mm whereas it only reached 2.5 mm for piles in section 2.

The maximum displacement value for piles in section 1 was greater than that of piles in section 2 and this was expected as three rows of tie back anchors were used to support the piles in section 2 whereas only prestressing strands were used for piles in section 1. However, the maximum horizontal displacement value at top of piles in both sections did not exceed the maximum allowable displacement determined for this project which was 30 mm. The results of this experiment indicate that cantilever piles with prestressing strands could successfully retain a 10 m deep excavation with allowable maximum horizontal displacement value. Since this value is within allowable limits, no damage is expected to occur in this shoring system nor in its surroundings. The prestressing effect played an important role in limiting the displacement of cantilever piles. The effect of prestressing was stored in the concrete section through the bond between steel strands and concrete. It increased the section's stiffness resulting in displacement decrease. Accordingly, this technique could be a possible alternative for tie back anchors in this excavation and in the existing soil conditions.

V. CONCLUSION

In this experiment, prestressing technique is proposed to minimize the displacement in concrete shoring piles retaining a deep excavation. This technique aims to improve the performance of cantilever shoring systems without using lateral support such as tieback anchors or struts. An experimental study was carried out in this paper about this technique during the execution of an open excavation in an urban area. Monitoring was performed at various construction stages using instrumentation technique (inclinometer). The obtained measurement results were found to be within tolerable limits.

This study indicates that the proposed technique returns sufficient rigidity, stability and strength preventing excessive pile displacement. The framework of this study reveals only an experimental approach for the soil condition prevailing, the current depth of the excavation and material properties. However, further experimental work on different site conditions in addition to numerical analyses are necessary to draw complete conclusions about this technique. It is also necessary to evaluate the reliability of the proposed technique by numerical analysis to provide further recommendations.

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