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Full Scale Modeling of Footing Supported on Expansive Soil using Concrete Pile Anchor Foundation (CPAF).

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Abstract: Buildings constructions over expansive soils are exposed to many problems and cracks. The most damaging issues occur due to differential heave displacements, which cause excessive deformations to the overlying structure up to and beyond its serviceability limit state and, in the worst cases, its ultimate limit state. A site investigation is performed for the study area at Tabuk University, Kingdom of Saudi Arabia. The geotechnical soil properties and swelling characteristics were determined. Visual observations of samples obtained from drilled boreholes at study area revealed reddish brown to grey thinly laminated weathered shale followed by shale formation, the subsurface formation is classified (CH) according to USCS. The research study is aimed at measuring the contact pressure at field and studying the efficiency of concrete pile anchor foundation (CPAF) system in reducing heave of footings constructed on expansive soil. In the field, two full scales reinforced concrete footings with and without concrete anchor piles were constructed on top of the expansive shale. After construction of field prototypes, the test area is wetted for 64 days. Monitoring of the footing movement indicated that the footing upward movement using CPAF system caused a 62% less than the footing constructed directly on expansive shale.

Keywords: Expansive soil, footing, concrete pile anchor, heave, pressure cell

I. INTRODUCTION

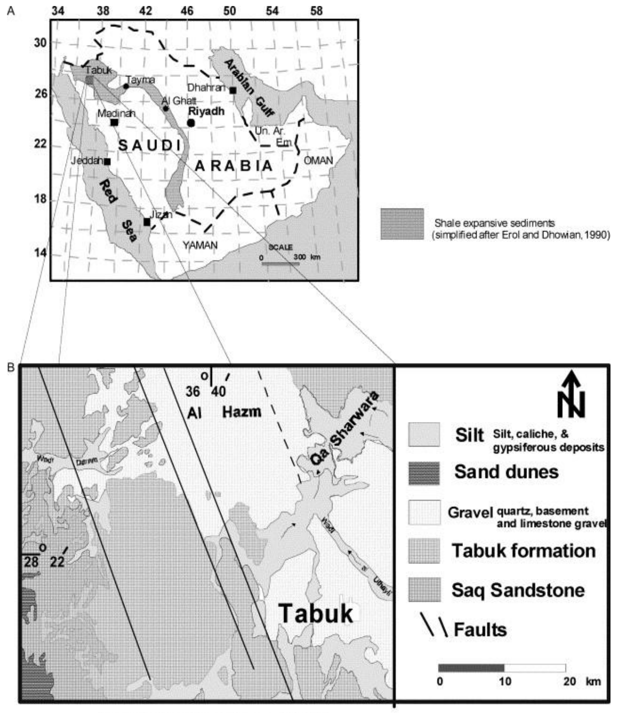
Light weight reinforced concrete structures over expansive soils may be subjected to significant upward movement which may cause undesirable cracks in the structure. Repair activities for these cracks should be repeated annually and in some cases the cost is significant. In some locations, the estimated damage cost attributed to soil expansion exceeds the cost of damages from natural disasters such as floods, tornadoes, hurricanes, and earthquakes [1].

Expansive soils cover a vast area of the Kingdom of Saudi Arabia (KSA) about 800,000 km^2, the expansive soils in Saudi Arabia can be identified as clayey shale formations, clay, and calcareous clayey soils. Clayey shale formations are encountered in cities Al Ghatt, Tymaa, Tabuk, and Tabarjal. Clayey soils are located in a Madina, and calcareous clayey soils prevail in the eastern region of the Saudi Arabia [2].

At the Kingdom of Saudi Arabia, the expansive soils were reported in several locations including Tabuk city (Fig. 1). Shall formation at Tabuk city, Saudi Arabia is the source of expansive soils due to the presence of clay minerals (smectite and illite) that are derived from the weathering of the shale [4,5,6].

Al Sabtan [3] performed X-ray tests on number of selective shale samples at Tabuk city, these tests indicated that the soils contain kaolinite followed by illite, and a smaller percentage of montmorillonite (smectite group), so they will have significant swelling potential when wetted. The soil expansion degree at Tabuk ranges from low to very high. These soils undergo significant change in volume (swell and shrinkage) due to changes in moisture content. At Tabuk city, different forms of damage are seen in Al Maseef, Al Nahdah and Al Rowda districts is estimated in hundreds of millions US dollars. Light weight buildings, pavements and mosques that are founded on this kind of soils were subjected to up-heave forces which resulted in serious cracks, tilting and twisting.

Understanding the expansive mechanism and the factors affecting the swelling behavior was studied extensively [3,7,8,9,10]. The swelling of soils is due to the presence of expanding clay minerals, such as smectite, that absorb water, the more content of this clay causes higher soil swell potential. The swelling behavior related basically to the geotechnical properties include the moisture content, Atterberge limits, and dry density. The environmental factors include the confining pressure, type and degree of weathering as related to the amount of clay fraction [11].



(After Bramkamp et al., 1963)

Fig. 1. Distribution of expansive soil at Tabuk City [3].

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To eliminate the effects of expansive soils, different design alternatives for foundation of light weight structures are presented in the literatures. The proposed design methods are involved in using of stiffened foundations, placing isolated footings at depths exceeding the depth of seasonal variation of moisture content [12], use of replacement soil [13], stabilization by Chemical agents using cement, lime, and fly ash [14,15], micro piles [12], stone columns [16] and granular pile anchor [17,18].

CPFA system is a foundation technique used in mitigating the heave of expansive clay and improving their engineering behavior. Concrete piles are a well-known foundation system used for reducing the settlement and increasing load-carrying capacity of soft clay beds [11]. In the CPAF system, the foundation is anchored at the bottom of the concrete pile to an anchored steel plate with the help of a mild steel rod. This renders the concrete pile to be tension resistant and enables it to offer resistance to the uplift force exerted on the foundation by the swelling soil.

Figure 2 shows a typical schematic representation of the fundamental concept of a concrete pile anchor foundation (CPAF) system and the various forces acting on the foundation. The uplift force acting on the base of the foundation in the vertical direction is due to the swelling action of the expansive soil. This uplift force is resisted by the weight of the concrete pile acting in the downward direction. The upward movement of the foundation is resists by the friction mobilized along the pile-soil interface and the anchor in the system. The upward resistance is further augmented by the lateral contact pressure, which increases the friction along the pile soil interface. The swelling action of the saturated soil is mobilizing upward friction forces. In this research study, the efficiency of CPAF system in heave reduction of field model constructed on expansive soil in City of Tabuk, Saudi Arabia was investigated in this paper.

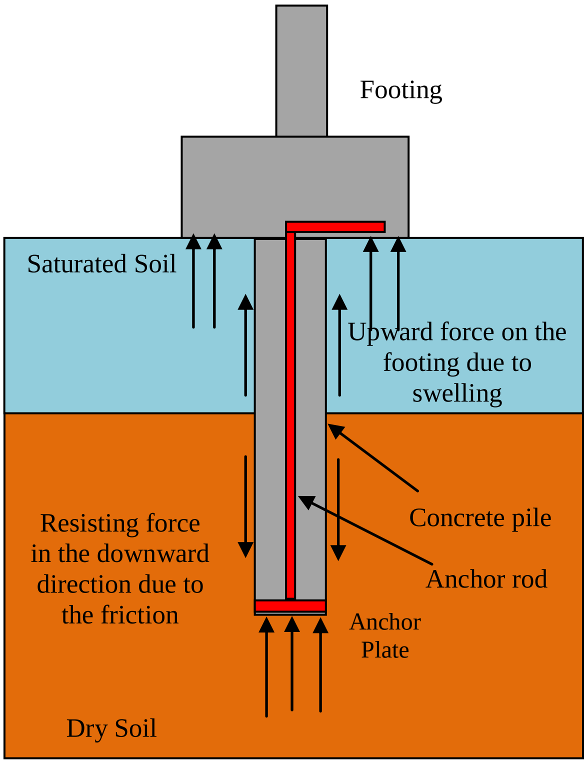

Fig. 2. Concept of concrete pile anchor foundation (CPAF) system

II. METHODOLOGY

This research focuses on measuring the reduction achieved by using CPAF on heave of footings caused by soil swelling. Figure 2 illustrates the footing and the CPAF system. Two reinforced concrete footings are constructed at a site in Tabuk City, K.S.A. The first footing was constructed as a regular footing and the other one as CPAF system. Surveying instruments are used to monitor the heave in footings along the period of 64 days where the site is submerged by water. An earth pressure cell is installed below the regular footing to measure the in-situ contact pressure. Strain gauges are installed on the anchor rod for determination of the force mobilized in the anchor rod due to the resistance of the action of the swelling soil.

III. DESCRIPTION OF FIELD WORK

Work strategy includes soil investigation of testing area, determination of the geotechnical soil properties at laboratory, and construction of field models.

3.1. Site Stratigraphy and Laboratory testing:

The field model was constructed within bounds of the University of Tabuk – Ladies Campus in Al Maseif District, northwest of Tabuk. An approximate location of the site was shown in Figure 3. This site was selected due to structural damages observed in campus building attributed to expansive shale.

Fig. 3. Testing area location at girls university, Tabuk – Saudi Arabia.

Prior to test construction of field model, a borehole was drilled at testing test location to depth of 8.0m. The subsurface layers encountered at the site are illustrated in Figure 4. Additional four boreholes drilled at the testing location to depths ranging from 15m to 20m confirmed the presence of shale formation that extended to the maximum drilled depths. Visual observations of samples obtained from boreholes classified as laminated weathered shale. From the laboratory testing program, summary of geotechnical characteristics is presented in Table 1.

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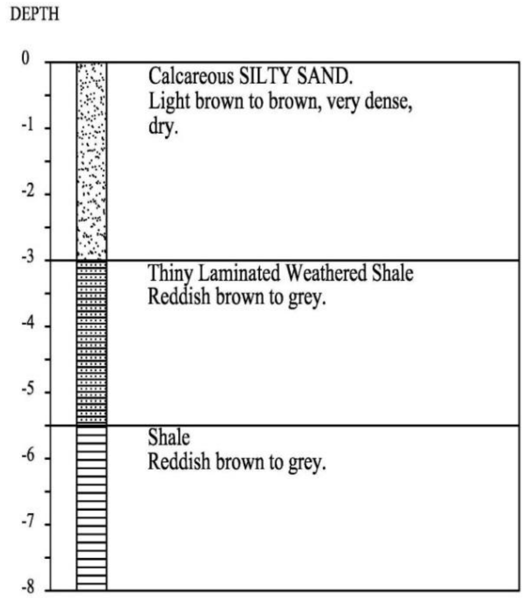

Fig. 4. Sub-surface layers log

Table 1. Physical properties of natural soil

Property	Value
Dry density (gm/cm^3)	1.7
Specific gravity	2.76
Natural water content (%)	3.1
Liquid limit (LL) %	55.7
Plastic limit (PL) %	25.2
Plasticity index (PI) %	30.5
Shrinkage limit (SL) %	19.6
Degree of saturation (S) %	14.0
Sand content %	6.7
Silt content %	52.3
Clay content %	41.0
Clay activity(A)	0.74
Swelling pressure (kN/m^2)	120
Free swell %	97
USCS : Unified Soil Classification	CH

3.2 Field Prototypes Construction:

The field work involved constructing of two full-scale reinforced concrete footings on top of the expansive shale layer encountered at the test site (i.e., foundation level is approximately 3.5 m below ground surface). First footing was representing a regular footing, while the other simulates the CPAF system with four concrete pile anchors at spacing of 1.0 m center-to-center as shown in Figure 5. The concrete pile anchors had dimensions of 2.0 m depth and 0.2 m in diameter.

Construction sequence of concrete pile anchors involved hole drilling using a machine driven auger and compressed air, placement of steel anchor. Before installment of steel anchor, the drilled holes were cleaned well from dusts. The steel anchor comprised of a steel bar with a steel plate welded to one of its ends. The anchor was extended above foundation level to ensure anchorage to concrete footing as shown in the model schematic drawing in Figure 5. A sand trench of 0.3 m width and 0.4m depth was dug around the footing as shown in Figure 6 to facilitate the infiltration of water into the expansive soil underneath the footings. Finally, reinforced concrete footings have plan dimensions 2.0 m x 2.0 m and thickness of 0.40 m, reinforced with top and bottom steel reinforcement mesh of 5Φ12 mm/m and had a yield stress of 420 MPa were casted in place as shown in Figure 7, using ready-mix normal weight concrete with a target compressive strength of 25 MPa after 28 days.

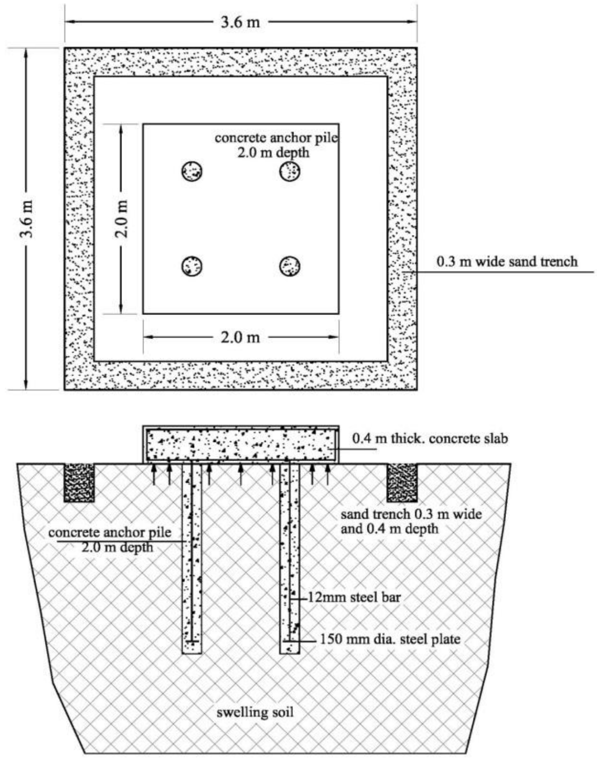

Fig. 5. Schematic drawing for footing supported by CPAF system

Fig. 6. Preparation of footing location

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Fig. 7. Field footing model

Fig. 8. Earth pressure cell installation

IV. INSTRUMENTATION AND MONITORING

The CPAF model was instrumented using pressure cell and strain gages for the evaluation of the field contact upward pressure and studying the effect of using CPAF technique on the heave reduction behavior founded on clayey shale formation.

4.1 Survey works

Monitoring the heave of constructed full scale models along test period had been performed by fixing five points on the top of footing surface. The monitoring process was carried out using calibrated surveying instruments. The footings heave due to swelling action was monitored to evaluate the efficiency of anchor pile type in reduction of upward movement due to soil swelling. The footings heave was monitored along test period two times weekly for the first 30 days and one time weekly thereafter and till end of test period.

4.2 Strain gages

In order to measuring the strain deformations occurred in steel bar of anchor rod due to the swelling action of the expansive soil. Four strain gages were fixed on the top of the steel bar of the anchor to measure the tension force resisted by the anchors rods. The strain were recorded daily using a read out daily for first 7 days and then periodically every two days till end of test period.

4.3 Earth pressure cell

The model representing the regular footing was instrumented with an earth pressure cell to measure the in-situ contact pressure underneath the model. The change in contact pressure along the period of test was monitored three times weekly. Earth pressure cells are designed to measure stresses in soil or the pressure of soil on structures. The earth pressure cell used in this research was the hydraulic type. Installation of the earth pressure cell is shown in Figure 8.

V. FIELD ACTIVITIES AND MONITORING OF RESULTS

The testing area of field models was continuously flooded with water for 64 days. The thickness of shale layer that absorbs water was increased with time and the vertical movement of slabs and contact pressure beneath the footings is observed to be increased. At the end of field testing period, one borehole was drilled using compressed air inside the testing area to investigate the depth of infiltrated water beneath the slab which was found 0.90 m below the bottom of the footings.

5.1 Contact pressure measurements

The contact pressure measured at the end of test period was 49 kPa. Figure 9 shows the evolution of the contact upward pressure underneath the footing with time during test period. The measured swelling pressure using the conventional oedometer test was found 120kPa which is much higher than the observed field contact upward pressure. The measured field upward contact pressure was about 40% of the predetermined swelling pressure in the laboratory using the conventional oedometer test.

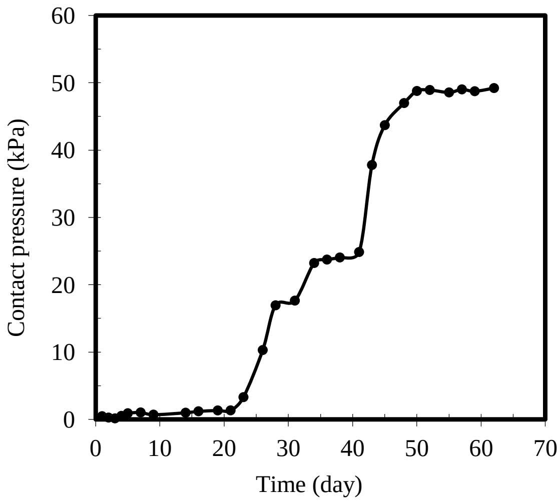

Fig. 9. Pressure cell measurements along test period

5.2 Upward movement of field models

Monitoring the heave of the two constructed footings had done using surveying instruments; the elevations of five points on each footing surface were monitored along the test period.

The average upward displacements of these points for the two models are displayed in Figure 10. At the end of wetting period, the average measured upward movement of the regular footing model was found 125 mm, while the measured upward movement of footing model representing the CPAF system was 47 mm. the total displacement reduction of CPAF model was about 62%. It is important to note that the infiltrated water depth beneath the field prototypes was measured 0.90 m at end of test period.

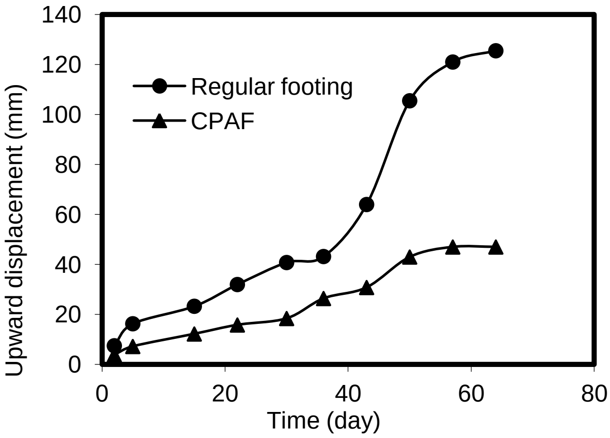

Fig. 10. Effect of pile anchor type on slab-on-grade displacement

5.3 Strains in anchor rods.

The anchor steel rod resisted the tension mobilized from the uplift force due to the contact pressure. The tension strains are occurred in steel bar of four pile anchor measured continuously along the test period. Figure 11 displays the tension strains measured by the strain gages during the test period. From Figure 11, the concrete pile anchors resisted the uplift forces till 28 days in concrete pile anchors have strain gages numbers (1&2), and resist the uplift force through period of 31 days in pile anchors have strain gages numbers 3 and 4. The maximum strain values in micro strain unit for steel bar in the concrete anchor piles shown in Table 2. By considering steel young's modulus is equal to $2E10^8$ kN/m^2, and concrete young's modulus is equal to $2E10^7$ kN/m^2, the stresses mobilized along anchor rods can be determined through the equation ($\sigma = E\mathcal{E}$), the determined stresses and uplift forces values in pile anchors are shown in Table 2.

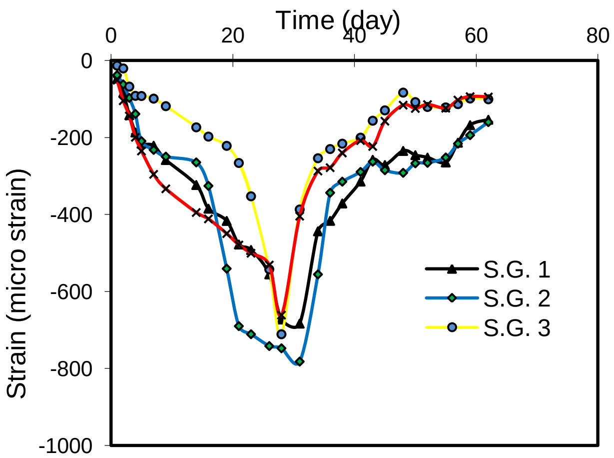

Fig. 11. Strain gages measurements of CPAF slab model

Table 2: Strain, stress and uplift forces in concrete pile anchor steel bar

Strain gage no.	Strain (με)	Stress in anchor bar (kN/cm^2)	Pile Resistance Force (kN)
1	672	13.4	15.1
2	782	15.6	17.5
3	711	14.2	15.9
4	661	13.2	14.8

The average measured pile axial tension force is 15.8 kN.

VI. CONCLUSIONS

Field testing modeling was conducted to study the performance of the CPAF against the swelling behavior of expansive soil formation at field. This study focuses on studying the efficiency of CPAF system in minimizing heave of footings that founded on expansive clay. The main conclusions that can be derived from this study are summarized as follows:

1. Swelling pressure determined at laboratory was determined 120 kPa, while the measured contact upward pressure at field along test period was 49 kPa.
2. As presence a difference between the determined swelling pressure value from the oedometer test results and the measured contact upward pressure at field by earth pressure cell, it is recommended to measure field contact pressure at site soil investigation period performing at least one test or consider the expected contact upward pressure at site is equal 40% of determined swelling pressure from the oedometer test results.
3. Installation of concrete pile anchors in expansive soil reduces the amount of heave effectively. At field model of slab on-grade supported on concrete piles, the upward slab displacement caused due to the swelling effect reduced the by 62%.
4. Heave reduction in CPAF system can be attributed to the frictional resistance mobilized along the pile-soil interface, the effect of anchorage which renders the concrete pile to be tension resistant and enables it to resist the uplift force exerted on the foundation. In addition, the upward resistance is augmented by the lateral pressure that increasing the friction along the pile soil interface, and increase the uplift resistance.

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