International Journal of GEOMATE, Aug., 2022, Vol.23, Issue 96, pp.32-39
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2022.96.3074
Geotechnique, Construction Materials and Environment

GEOTECHNICAL INVESTIGATION OF ARID CLIMATE SOILS FOR IMPLEMENTING SOLAR TRACKERS

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ABSTRACT: Stability and well-designed foundations are the most important requirements of a solar tracker when utilizing fixed and single and dual-axis tracking systems. This paper examines the results of a comprehensive geotechnical investigation into the implementation of solar tracker systems in Kuwait, along with significant geotechnical insights into solar photovoltaic energy. The study includes several laboratory tests on basic soil properties, as well as a Standard Penetration Test (SPT) and Field Plate Load test to compute the bearing capacity of the soil. The test results indicate that the soils are capable of supporting shallow foundations, with a minimum depth below the ground surface of 1.0 m. In addition, the bearing capacity calculations and the Plate Load Tests (PLT) highlight a bearing capacity of approximately 200 kPa for 1.0 m depth and 300 kPa for over 2.0 m in response to the cemented sand layers below the ground surface. This is due to the low permeability of the soil (i.e., 1.8 x10^{-6} m/sec) and the strength parameters. The geotechnical investigation indicates the presence of adequate soils with high bearing capacity and low degree of settlement, thus confirming the site's applicability for the use of solar tracker systems.

Keywords: Stability, Solar tracker, Geotechnical investigation, Solar photovoltaic energy, Bearing capacity

1. INTRODUCTION

The implementation of solar photovoltaic technology for the production of electricity has recently demonstrated several encouraging results. However, it remains vital to devedevelop methods of increasing the performance of solar photovoltaic systems. Solar modules are placed on the roofs of buildings or mounted on solar structures in farms or parks in many countries (i.e., the United States), demonstrating a preference for ground-mount systems [1]. In addition, the use of solar tracking systems has proved highly effective due to their ability to adjust to the optimal position allowing them to receive the maximum amount of solar irradiance. Following sunlight with optimum tilt angles has been estimated to result in between a 30% and 40% increase in solar irradiance when using tracking systems as opposed to fixed tracking systems [2], [3]. The most popular systems currently in use are single and dual-axis tracking systems, as shown in Figure 1.

The economic importance of solar tracker systems is demonstrated by solar modules (which represent approximately 55% of the total cost of any photovoltaic system) being supported by the solar tracker. Thus, should the solar tracker be damaged or fail (i.e., due to an extreme wind load or excessive ground settlement), there will be an impact on the system and the solar modules in particular? This demonstrates the need to establish an effective design of foundations, one capable of addressing differing environmental factors and ensuring stability [4].

The use of single and dual-axis tracking systems has had a significant impact on the performance of photovoltaic systems. A large number of studies have found that the use of tracking systems tends to increase the amount of produced energy by over 30% and 40% in comparison to fixed tracking systems[2], [3]. In Kuwait, the production of energy has increased significantly (i.e., by 24% and 30%) through the use of single and dual-axis tracking systems, respectively [5]–[8].

However, it is important to highlight that solar photovoltaic energy is comprised of multidisciplinary scientific curriculums (i.e., electrical, mechanical, and geotechnical engineering), all of which possess guidelines and basic principles for renewable technologies. This current study focuses on the investigation of soil properties to determine the most suitable foundations for solar trackers.

The stability and reliability of the solar structure are crucial for the safe use of the solar tracker, particularly regarding aerodynamic loads, as well as increasing the degree of solar irradiance [4], [5]. The main factors to be considered when selecting the foundation of a solar tracker are the soil properties of the ground and appropriate structure design for the materials and structural elements employed [4], [9].

The design of the foundations for solar tracker structures has similarities with all other constructions, i.e. the selected footing should be able to withstand firstly its weight and, secondly, wind loads [5].

There are many types of foundations for mounted solar structures, i.e. driven and helical piles and isolated shallow foundations. Their use is dependent on various factors, including economic and technical. A key aspect of this current study concerns the geotechnical properties of the ground, indicating the importance of understanding the behavior of soil using foundation design [10].

In general, steel pipes partially embedded in the ground are used to support typical solar photovoltaic systems, which are distributed in rows to comply with their electrical configuration systems [11]. In addition, steel piles are widely used to support solar trackers on the ground. There are several different types of piles, including; (1) concrete piles; (2) precast concrete piles; (3) cast-in-pace piles; (4) driven piles; and (5) helical piles [1]. Of these, helical piles are the most widely used foundations for lightweight structures and solar panel trackers [12].

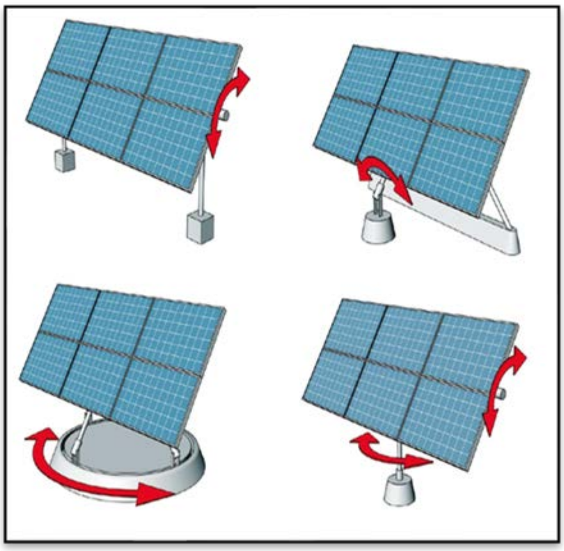

Fig. 1 Different tracking systems [5], [23]

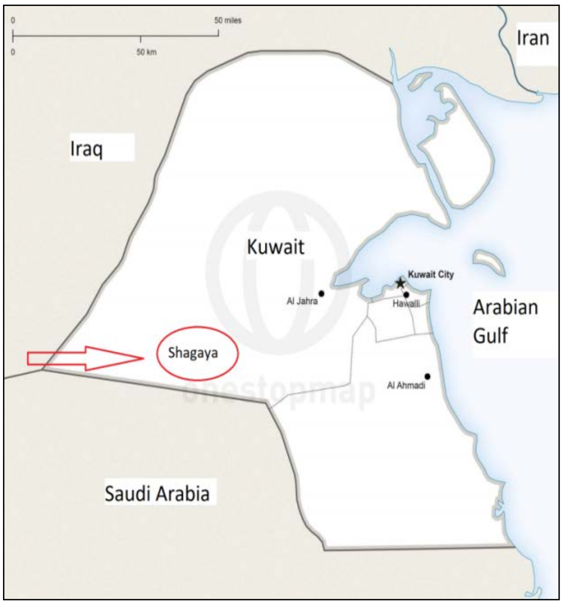

Fig. 2 location of the Shagaya area on Kuwait map

Extensive information and data are required to perform a geotechnical investigation for any site, including a description of the soil layers and basic soil properties, along with the details of the soil layers, i.e. thickness, soil classification, and strength parameters. Field data is also important, demanding the need for more advanced soil tests to check (or determine) specific parameters. The laboratory and field tests of a site are analyzed and verified using local and international codes and specifications, leading to the creation of a numseveralificant results. This should be considered an important step in identifying the most appropriate materials and design method for each project, i.e. the type of foundation required. In addition, more detailed and extended recommendations can be established, taking into account both the circumstances and type of projects. For example, more detailed clarifications and feasibility studies can be conducted to establish methods and techniques capable of enhancing the performance and efficiency of any proposed system.

This current paper, therefore, introduces the results of both laboratory and field tests examining the geotechnical properties of arid climate soils facilitating the installation of photovoltaic solar trackers in the Shagaya area of Kuwait. The investigation focussed on: (1) basic soil properties (i.e. relative density, moisture content, grain size distribution, and direct shear test) and (2) a plate load field test. The testing program included all the required data and parameters for foundation design. This study will thus provide a benchmark and solid reference for any future engineering works about the geotechnical properties of the proposed site.

2. RESEARCH SIGNIFICANCE

The use of solar mounting structures, particularly single and dual-axis solar trackers, is increasing over the world. These types of solar photovoltaic systems are characterized by gaining the maximum allowable solar irradiation throughout the day by tracking the sunlight in the best position.

Solar tracking systems used in open areas such as deserts need to be installed by foundation systems. This research aims to provide a solid base of information for the stakeholders of the solar photovoltaic systems using the geotechnical investigation of the sites where those systems were installed, and are popularly in Kuwait.

3. METHODOLOGY

3.1 Site Location and Ground Condition

The state of Kuwait is a member of the Gulf Cooperation Council (GCC), located in the Middle East of the continent of Asia. The surface of Kuwait is characterized by dominant windblown dune sand, having various layers, up to 7 m in depth, underpinned by fine to medium sand deposits, which are supported by approximately 90 m of limestone bedrock [5], [13]–[15].

The proposed site is located in the Shagaya area, in the southwest of Kuwait, being 60 km from the capital, Kuwait city, as shown in Figure 2. The Shagaya area is characterized by desert terrain with a surface of sandy soils [16].

3.2 Data Collection

The geotechnical data (in particular, the properties of the soils) were collected from the Kuwait Institute for Scientific Research (KSR)[17]. The data originated from boreholes at the Shagaya site, using boring auger techniques, with the samples collected using split-spoon samplers at different depths below ground level. In addition, bulk samples were extracted at the surface and various depths below ground level using manually drilled testing pits. The testing program was divided into parts, with tests firstly conducted in the laboratory and secondly at the site. The laboratory tests included all basic tests, i.e. (1) specific gravity; (2) unit weight; (3) moisture content; (4) grain size distribution; (5) Atterberg limits; (6) permeability by the falling head test method; and (7) compaction parameters (OMC & MDU) by modified Proctor test. The collected samples were tested laboratory-based based on ASTM standards.

To maintain representative data, the field test program employed the Standard Penetration Test (SPT) and the Plate Load Test (PLT) at separate locations.

3.3 Basic Soil Properties

The soil samples collected from the field were placed inside plastic tubes to maintain their properties and minimize the impact of sampling disturbance. The basic soil parameters were determined, with the soil classification based on the Unified Soil Classification system and the American Association of State Highway and Transportation Officials (AASHTO). Table 1 lists the results for classification and Table 2 lists the results for the soil properties established in the laboratory. The modified proctor compaction test and direct shear test were conducted on the collected samples according to ASTM D1557 and ASTM D3080, respectively [18], [19]. These tests represent strength parameters, i.e. soil cohesion and the angle of internal friction. The Plate Load Tests were conducted in the field to estimate the bearing capacity of the soil. They were employed according to ASTM D 1196-94.

3.4 Strength Parameters

A direct shear test is a laboratory test considered in this study to measure the shear strength properties of the soil at the proposed site. A set of direct shear tests were conducted to determine the strength parameters (cohesion (c) and the internal angle of friction (ϕ)) according to ASTM D3080 [20]. These parameters were used to calculate the expected bearing capacity of the soil and other geotechnical engineering purposes.

3.5 Bearing Capacity

To design a foundation, it is important to (1) determine the bearing capacity of the soil layers and then compare them to the expected loads transmitted from the structural design stage and (2) specify the type of foundation, i.e. shallow or deep. In addition, this forms an essential step in locating the embedment depth of the footing.

As a result of his field studies, Meyerhof published several well-known equations to determine the permissible bearing capacity for a 25mm settlement [21]. T. allowable bearing capacity of the soil can be determined about pt which is a widely used field method and was employed in this current study to calculate the bearing capacity (QA of the soil.

The following equations were used to compute the allowable bearing capacity for a 25 mm settlement [21]:

$$q_a = \frac{N}{0.08} * \left(\frac{B+0.3}{B}\right)^2 * K_d \quad \text{For} \quad B > 1.2\text{ m} \tag{1}$$

$$q_a = \frac{N}{0.05} K_d \quad \text{For} \quad B < 1.2\text{ m} \tag{2}$$

$$K_d = 1 + 0.33\left(\frac{D}{B}\right) \tag{3}$$

Where, N is the SPT value, K_d is the depth factor, B and D are the footing width and depth, respectively.

3.6 Foundation Design

It is generally accepted that one of the basic principles of foundation design is to ensure protection against shear failure and excessive settlement [22]. Thus, foundation design should consider the static load of a superstructure, including safety factors relating to bearing capacity failure and any settlement of the underlying soil.

In general, the design of foundations is subjected to factors concerning soil properties and the loads that the proposed structure is expected to carry.

The type of soil layers also forms an important factor specifying the type of foundation employed, along with the method used during the analysis and design stage. For example, it is more important to consider the issue of primary consolidation settlement when designing for clayey soil as opposed to sandy soil. An additional factor is the types of loads, particularly for solar tracker systems, which are exposed to wind loads. The fact that wind loads change over time in both magnitude and direction prompts designers to consider a variety of engineering issues. These include fatigue failure resulting from cyclic loadings of aerodynamic loads, which can cause failure in the structural elements, with the induced stress amounting to less than the ultimate stresses of such elements.

A further key point of foundation design is the bearing capacity of the soil, which requires consideration of many design parameters, i.e. the type and embedment depth of the proposed foundation.

On the other hand, it is vital to consider numerical modeling methodology when investigating the behavior of the ground and the proposed foundations in relatiaboutn weights and aerodynamic loads. This can be undertaken through advanced finite element software packages, which are widely available and have been used in many investigational studies.

In this current research, a set of Plate load tests were performed at the bottom of the test pits below ground level, using a steel plate 0.3 m in diameter. The recommendations for the most suitable foundations for the solar trackers are based on the results.

Table 1 Test results for classification

Sample at	% Gravel	% Sand	% Fines	LL	PL	PI	Classification
surface	0	98.9	1.1	NP	NP	NP	Poorly graded sand (SP)
depth 3 m	2.3	74.6	23.1	NP	NP	NP	Silty sand (SM)
depth 10 m	4.1	87.6	8.3	NP	NP	NP	Well graded sand with silt (SW-SM)
depth 12 m	0	87.2	12.8	36	21	15	Clayey sand (SC)

Table 2 Properties of the soil layers

Layer	Unit weight (kN/m^3)	Cohesion (kN/m^2)	The angle of internal friction (ϕ)	Modulus of Elasticity (MPa)
0- 3 m	18.38	15	32	10
3-10 m	19	16.79	39.2	40
>12 m	20	19.14	41.6	100

4. RESULTS AND DISCUSSION

This section outlines the detailed results of the comprehensive laboratory and field tests. In addition, it examines the main results to establish a complete understanding of the soil properties and main soil parameters required for the data analysis process. The analysis offers several recommendations, including the condition of the soil layers. Table 2 summarises the basic properties of the soil, revealing that both the unit weight and the cohesion of the soil layers increase by depth, indicating the cementation bond between the soil particles in this arid area.

The borehole investigation revealed that both the surface and subsurface investigations for the Shagaya site found granular soils. This was primarily sandy soil, which varied between poorly graded clayey sand (SC), silty sand (SM), and poorly graded sand with silt (SP-SM) using a unified soil classification system (USCS). The classifications tests were conducted according to the Unified Soil Classification System (USCS). Figure 3 shows the grain size distribution graph for the four samples collected at the surface and at a depth of 3 m, 10 m, and 12 m. The sand is the dominant size and the percentage of gravel and fines vary between 0 to 4.1% and 1.1 to 23.1%, respectively. The fine particles are maintained, demonstrating the different percentages with which silt increases with an increase in depth. This could explain the cementation bond between the soil particles, as well as the cohesion between the soil particles. It was not possible to establish the groundwater level during the borehole test investigations. This could be attributed to, firstly, the distance between the investigated site (which is in aran id desert area) and the sea, or secondly, a lack of accessible groundwater. The soil profile was comprised of: (1) medium dense, fine to medium-grained, silty sand, light brown to a depth of 3.0 m; (2) a very dense, fine to coarse-grained, well-graded sand with silt to a depth of 8.0 m; and (3) a very dense, fine to medium-grained, silty clayey sand to a depth of 13 m. This accords with the results obtained from laboratory tests. In addition, the standard penetration value (N) varies between 12 and 39, before increasing with depth. As stated above, this can be attributed to the cementation of soil layers beneath the surface. The degree of cementation increases with depth leading to an increase in SPT value, with some being over 50. However, the SPT value for anything over 50 was considered 50. Figure 4 presents the direct shear test graph undertaken with five different samples. The average cohesion was 15kN/m^2 and the internal angle of friction was 35°. The modified Proctor compaction test was performed for five different samples collected from a depth of 1.0 m. Figure 5 shows the modified compaction tests. It can be seen that the maximum dry unit weight varies between 17.51 to 19.57 kN/m^3, with an average of 18.54 kN/m^3. In addition, the optimum moisture content varies between 9.9 to 12.5%, with an average of 11.2%. The obtained average of the laboratory test 1900 kg/m^3 (18.64 kN/m^3) is in agreement with the in-situ dry unit weight. It should be noted that it is common practice in the state of Kuwait for relative compaction to consist of 90% for building structures and 95% for transportation work. The coefficient of the permeability of the soil ranged between 1.75 x10^{-6} m/sec to 9.49x10^{-6} m/sec, with an average of 2.85 x10^{-6} m/sec using the falling head permeability test. The permeability coefficient decreased with depth for the sample collected from different depth layers. This value is considered to be relatively small and can be attributed to the cementation bond between the soil particles to obtain more accurate results for Plate load tests, an average of three tests was employed. The tests were performed at a depth of 1.0 m below the ground surface. Three Plate load tests of 0.3 m diameters were conducted at this level with an adequate distance between the test locations at the site.

The impact of cementation of the soil grains at the embedment depth of the circular plate test was found to be insignificant due to this level being close to the ground surface. The soil cohesion was therefore ignored when using the general bearing capacity. Figure 6 shows the stress versus settlement graph for the Plate load test. When using the slope tangent method, the average failure load for the plate was found to be 175KPa, with a corresponding settlement of 1.2 mm. from the pressure- settlement graph, and the punching shear failure was observed. The bearing capacity values were computed using the Terzaghi- Meyerhof equation, in which the safety factor equals 3.0. Table 3 shows the allowable bearing capacity values for the proposed foundations, assuming a square footing with a width of B. The use of pile foundation is another important alternative, as the solar trackers are subject to axial and uplift forces resulting from their self-weight and various wind loads. The selection of pile types is dependent on several factors, including the soil condition on the site as well as technical and economic issues, i.e. the availability and the cost of the piles. The soil properties and soil profile of soil layers extending for over 12 m below the ground surface refer to medium to dense soil layers. This indicates that bored piles would prove more effective than driven pile foundations. It also provides significant input data for use in different studies, i.e. numerical modeling analysis. This study recommends that future research should experimentally investigate the behavior of the ground about different types of solar trackers.

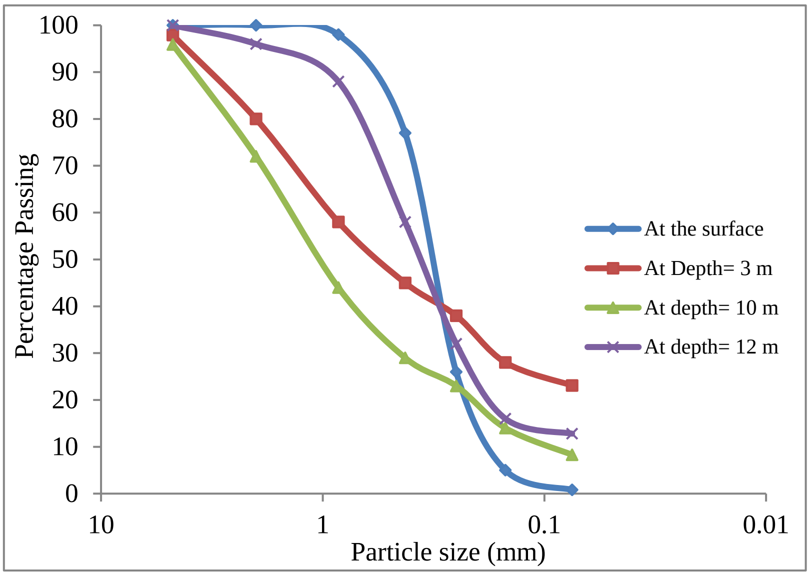

Fig. 3 Grain size distribution curves

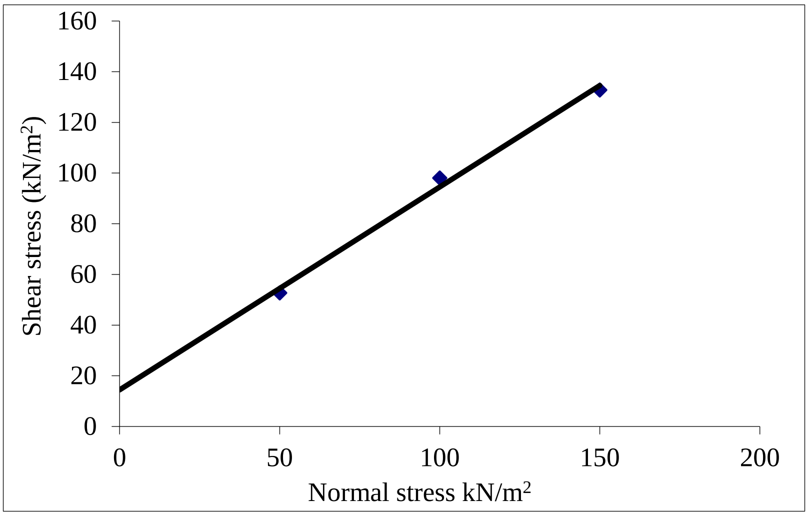

Fig. 4 Normal stress versus shear stress

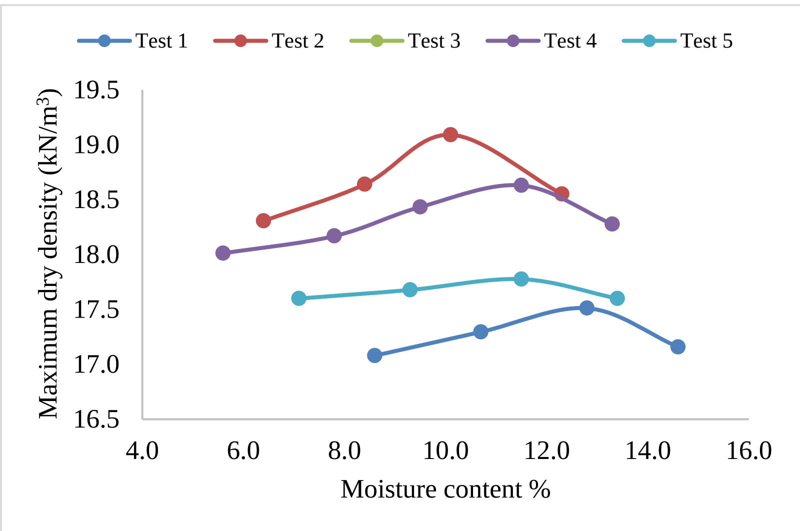

Fig. 5 Compaction curves for soil different samples

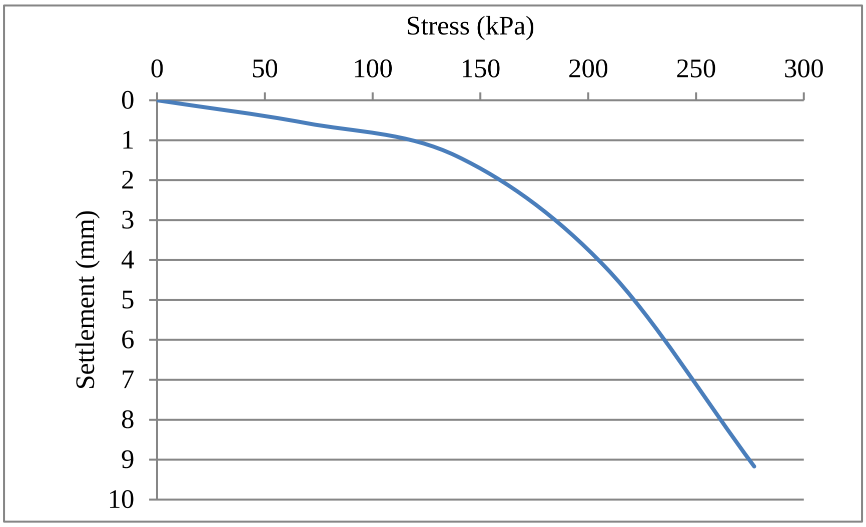

Fig. 6 Pressure-settlement curve

Table 3 Bearing capacity for the foundations

Depth (m)	Width (m)	Net allowable soil pressure for maximum 25 mm settlement (kN/m^2)
1.0	1 to 6	200
2.0	1 to 6	300
3.0	1 to 6	300

5. CONCLUSIONS

To investigate the applicability of implementing solar trackers in Kuwait, from a geotechnical engineering view, comprehensive laboratory and field tests were carried out at the Shegaya site in the state of Kuwait. The study included the basic soil properties. The field test program included the Standard Penetration Test (SPT) and the Plate Load Test (PLT). Based on the laboratory and field test results, the following conclusions and recommendations are drawn:

1. The proposed site is characterized by cemented soil and the unit weight and cohesion of the soil layers increase by depth.
2. The average coefficient of the permeability of the soil is equal to 2.85 x10^{-6} m/sec. This value is considered to be relatively small and can be attributed to the cementation bond between the soil particles.
3. The bearing capacity and Plate load tests revealed that the soils at the Shegaya site have a high bearing capacity of around 200 MPa for 1.0 m depth below the ground surface and 300 MPa for a depth of over 1.0 m.
4. It is recommended to carry out future research should experimentally investigate the behavior of the ground in different types of solar trackers.
5. This study provides an important opportunity for researchers and stakeholders in the field of solar energy to explore additional alternative options when it comes to selecting types of foundations for solar tracker systems.

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