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ORIGINAL ARTICLE

Undrained behavior of auger cast-in-place piles in multilayered soil

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Abstract Auger cast-in-place piles (ACIP) are often installed through multilayered soil profiles, which make accurate predictions of the performance of the piles more complex than piles constructed in either clay or sand deposits. This study is intended to shed some light on the undrained behavior of ACIP embedded in stratified soil and to explore a methodology to predict the ultimate pile loads. The study is based on practical measurements of load–displacement relationships of 51 static loading tests of full-scale ACIP installed through multilayered soil profiles. The study revealed that the normalized load–displacement relationships of the tested piles have deterministic range with upper and lower bounds. Equations for these bounds and the mean load–displacement relationship are developed in this study. There is a deficiency in the literature concerning the calculations of ultimate loads for piles embedded in multilayered soil. Therefore, this paper presents an attempt to estimate the ultimate pile load in undrained conditions utilizing two approaches. The first approach assumed the failure pattern of the soil beneath the pile base to be punching into the sand followed by general shear failure in clay underneath. The end-bearing resistance at the pile tip was estimated by implementing Meyerhof and Hanna's [24] shallow foundation procedure. The second approach assessed the depth of the influence zone below the pile tip using isobars of pressure around and below the pile tip due to a point load, based on the theory of elasticity and characterization of a semi-infinite soil mass (Martins [3]). Soil layers, within the zone of influence, were considered to be an equivalent geomaterial with shear strength parameters computed by weighted average of shear strength parameters of the soil sub-layers. For comparison purposes, the ultimate pile load of each test was interpreted experimentally using the method proposed by Chin (1970). Reasonable agreement was obtained between the predicated and the experimental values, with an accuracy of about $\pm 17\%$.

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1. Introduction

Although most theories of soil mechanics were developed by considering the behavior of either ideal clays or pure sands, in-field soil profiles do not confirm to either ideal soil type. In practice, auger cast-in-place piles (ACIP), also known as continuous flight auger (CFA) piles, are often installed

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through profiles consisting of multiple layers of soil. The literature concerning the response of axially loaded piles embedded in multilayered soil is sparse. Most of the studies pertaining to piles have dealt with piles embedded in either sand or clay [15]. Kim et al. [19] investigated the behavior of closed-ended pipe piles driven into stratified soil by conducting static and dynamic axial load tests on three piles. Seo et al. [32] presented the results of two static load tests on an H-pile driven into a silt-dominated multilayered soil profile.

Different approaches to analyze vertical piles under axial loads have been developed in recent decades. An approach was conducted assuming soil resistance along the pile shaft and at the pile tip can be represented by a series of independent springs [20,17,16]. The spring stiffness can be determined through theoretical, experimental, or empirical procedures. Another approach considered the soil as a continuum [26,21,22,31]. Furthermore, other approach was based on energy principles [4]. Seo et al. [30] combined the elastic continuum approach with the potential energy principle to predict the displacement of circular and rectangular piles in stratified soil.

The responses of single piles and pile groups under axial loads were studied using laboratory tests, centrifuge models, full-scale tests, and theoretical and numerical studies. The results of laboratory tests are usually affected by scale effects. Centrifuge models produce reliable results, but they require complex instruments and they are cost prohibitive. Full-scale tests are more representing to field conditions, however, they are expensive. Despite significant theoretical advances in the analysis and prediction of pile behavior in recent decades, static pile loading tests remain the most reliable means of assessing the response of single piles and pile groups under design loads [23]. Pile loading test results provide reliable data for reverse engineering that enable the engineer to confirm and refine appropriate soil strength, stiffness, and compressibility characteristics. Refined soil parameters make it possible to better understand and characterize subsurface conditions, justify and refine initial engineering assumptions, and improve final predictions.

Many studies of piled foundations have been based on gathering relevant databases. Dithinde et al. [12] presented four load test databases for driven and bored piles in cohesive and cohesionless soils to identify and also to quantify the uncertainties associated with various geotechnical design approaches. Chen et al. [8] established a database to evaluate the capacity of drilled shaft foundations under axial uplift loading. Based on pile load–settlement test data from case studies obtained from literature, Haldar and Babu [18] proposed a procedure to determine partial factors in a reliability-based design format for pile foundations. Schneider et al. [29] examined the predictive performance of a range of pile design methods using a compiled database of static load tests on driven piles in cohesionless soils.

The undrained behavior of auger piles depends principally on the type of soil through which the pile is installed. When ACIP are installed in stratified soils, they exhibit more complex behavior compared to those installed in uniform soils. The tip resistance, which may be affected by multiple soil layers located within the zone of influence of the pile base, is more difficult to analyze. Moreover, methods developed separately for clean sand and pure clay are also used for soils that contain various proportions of sand and clay. Therefore, both theoretical and experimental efforts should be made to develop a better understanding of the behavior of piles installed through multilayered soil profiles. This is the motivation for the research reported in this paper. The study sheds some light on this problem by analyzing the results of pile loading tests on 51 individual piles installed in multilayered soil. Each of the pile tips was embedded through a sand layer overlying a clay layer of limited thickness. To avoid the complexity of mathematical models and the uncertainties inherited in theoretical assumptions, the analyses were based on practical measurements of load–displacement relationships of the tested piles. An attempt was made to establish two procedures for the calculation of the ultimate pile load in undrained conditions. The study presents a comparison between the predicted results and the experimental values.

2. Description of soil profile

Pile loading tests were collected from 12 different construction sites at the city of Alexandria and nearby districts in Egypt. The database was limited to sites at which the pile tip was bearing in a sand layer overlying a clay layer of limited thickness, as shown in Fig. 1. In the studied sites, the clay is alluvial type and normally consolidated. Exploration programs were conducted at the construction sites using boreholes and retrieving representative soil samples to determine the subsoil stratification system and the geotechnical properties of each stratum. Soil samples were retrieved using a split–spoon sampler and Shelby tubes whenever possible. Standard penetration tests were performed in accordance with ASTM D 1586 during borehole sampling. The soil samples recovered were classified in accordance with ASTM D 2487. The depth of the stable groundwater table was measured in the boreholes 24 h after of the completion of soil sampling.

To establish the soil profile at each site, the soil classifications available from the boring logs were reevaluated based on the laboratory test results. Undisturbed soil samples obtained from cohesive soil strata were tested in the laboratory to assess the properties of the soil layers. Sieve and hydrometer analyses were conducted on representative samples from all soil layers in the profile. Atterberg limits and natural water content values were determined for the cohesive soil layers. Direct shear tests and unconfined compression tests were conducted to determine the shear strength parameters of the cohesive soils. Consolidation tests were performed on samples collected from cohesive soils. All tests were performed in accordance with relevant ASTM standard test methods. Table 1 summarizes soil stratifications and number of pile loading tests at each site.

3. Procedure for pile loading tests

Loading tests were carried out on working piles in accordance with the Egyptian code of soil mechanics and foundations [13]. The procedure entails a load cycle in which the pile is loaded in increments up to the design test load and then unloaded in a similar manner. For working piles, the test load is recommended to be one and one half times the working load. The test load was applied in six equal increments. The applied load increment was maintained using a calibrated hydraulic jack, and the vertical displacement of the pile head was measured