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Field Instrumentation and Testing to Study Set-up Phenomenon of Piles Driven into Louisiana Clayey Soils

INTRODUCTION

Piles driven into saturated cohesive soils (clays and silts) usually experience a time-dependent increase in pile resistance (mainly frictional), known as "pile set-up" or "freeze." Field observations showed that pile set-up is significant and continues to develop for a long time after installation, especially for fine-grained soils. The increase of pile resistance over time or set-up is believed to be attributed to three main mechanisms: (1) the increase of effective stress due to dissipation of excess pore water pressure generated during pile driving, (2) thixotropy, and (3) stress independent increase or "aging" after the completion of excess pore water pressure dissipation.

During pile driving, the soil around the pile (within an influence zone) undergoes large lateral deformations and disturbance, resulting in the development of excess pore water pressure around the pile and change in soil's permeability within the disturbed zone. It is believed that a large contribution to pile set-up is related to the dissipation of excess pore water pressures (or consolidation), and the subsequent remolding and reconsolidation of the soil within the influence zone. At early stages, the dissipation of excess pore water pressure can be non-uniform with respect to the log of time depending on soil permeability and extent of soil disturbance. After that, the dissipation becomes uniform. Following that, aging may account for an additional pile set-up. Set-up can occur in all pile types driven in different soil types (organic and inorganic, clayey, silty, and even sandy soils).

Several empirical relationships have been proposed to estimate the pile set-up resistance with time. Most of the available developed models did not consider the soil properties in the formulations and that the total resistance (R_t) was used instead of side resistance (R_s). Therefore, set-up prediction models that can estimate set-up at different soil conditions are needed. The accurate prediction/estimation of the increase in pile resistance with time (or set-up) can be incorporated into a rational design through reducing the number of piles, shortening pile lengths, and/or reducing pile cross-sectional area (using smaller-diameter piles). Incorporating any or a combination of these benefits will result in a cost reduction and savings to pile foundation design in Louisiana. The foundation cost will be reduced by substantial amount if load and resistance factor for set-up ($\Phi_{set\text{-}up}$) is incorporated successfully into the LRFD framework. Currently the American Association of State Highway and Transportation Officials (AASHTO) does not have any recommendation to incorporate set-up into the LRFD framework.

OBJECTIVE

The main objective of this research study was to evaluate the time-dependent increase in pile resistance (or pile set-up phenomenon) for piles driven into Louisiana soils through conducting repeated static and dynamic field testing with time on full-scale instrumented piles for the purpose of incorporating the pile set-up into DOTD design practice. This will include investigating the mechanism of pile set-up, studying the effect of soil type/properties, pile size, and their interaction on pile set-up phenomenon, and developing a model and its reliability to estimate the increase in pile resistance with time.

SCOPE

In order to implement objectives of this study, full-scale load tests were performed on different locations of Louisiana. A series of dynamic load tests and static load tests were conducted on each test pile in order to measure the amount and rate of set-up. The test piles were instrumented with different sensors in order to measure the side resistance of individual soil layers and understand the set-up phenomenon better. Vibrating wire strain gages were installed in pairs in all the test piles in order to measure the side and tip resistances separately and also measure the load distribution along the

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length of the piles. This load distribution along the length of the pile was used to measure the side resistance of individual soil layers. Skov and Denver's (1988) formulation was implemented to calculate the logarithmic set-up rate of individual soil layers. The logarithmic set-up rate "A" of individual clayey soil layers was correlated with different soil properties (e.g., undrained shear strength, plasticity index, coefficient of consolidation, sensitivity, and overconsolidation ratio). Regression analyses were performed with the aid of Statistical Analyses Software (SAS) program in order to develop the set-up prediction model with incorporated soil properties. Finally, load resistance factor calibration was performed in order to calibrate the set-up resistance factor.

METHODOLOGY

This research study aims to investigate the pile set-up phenomenon for clayey soils and develop empirical models to predict pile set-up resistance at certain time after end of driving (EOD). To fulfill the objective, a total number of 12 prestressed concrete (PSC) test piles were driven in different soil conditions of Louisiana. Detailed laboratory and in-situ soil testing were performed at each test pile location in order to characterize the subsurface soil condition.

Dynamic load tests and static load tests were performed at different times after EOD to verify the axial resistances of piles and to quantify the amount of increase in resistance (i.e., set-up) compared to the EOD. The focus of this research was to calculate the resistance of individual soil layers with time along the length of the pile. In order to implement this goal, all the test piles were instrumented with vibrating wire strain gages. The measurements of vibrating wire strain gages were used to measure the distribution of load transfer along the length of the pile during the static load tests. Vibrating wire piezometers and pressure cells were also installed in the pile face in order to calculate the time for dissipation of excess pore water pressure and corresponding increase in effective stress with time. The Case Pile Wave Analysis Program (CAPWAP) was performed in all the dynamic load test data and used to calculate the side resistance of individual soil layers along the length of the pile during dynamic load tests.

Logarithmic set-up parameter "A" of individual soil layers were calculated using the unit side resistance. The set-up parameter "A" was correlated with different soil properties such as undrained shear strength, plasticity index, coefficient of consolidation, sensitivity, and overconsolidation ratio (OCR). Three different levels of empirical models were developed to estimate the magnitude of pile set-up with time with two different initial normalized time, to (i.e.,1 hour and 1 day). The developed models were used to predict the total resistance of piles in the database at four different time intervals (i.e., 30 days, 45 days, 60 days and 90 days) after EOD. Reliability analyses were performed to calibrate the set-up resistance factor ($\Phi_{set\text{-}up}$) for incorporating it into the LRFD pile design methodology. LRFD calibration was performed by First order second moment (FOSM), First order reliability method (FORM) and Monte Carlo simulation method.

CONCLUSIONS

The testing program and the results of the SLTs and DLTs demonstrated that set-up behavior follows a linear logarithmic rate with time after EOD, similar to the Skov and Denver (1988) model for all the test piles. The tip resistances (R_{tip}) were almost constant, with the majority of set-up was mainly attributed to increase in side resistance (R_s). The piezometers that were installed on the piles' faces demonstrated that the dissipation of excess pore water pressure generated during pile driving correlates very well with the pile set-up process. Both the total resistances (R_t) of the piles and the side resistances of the individual soil layers exhibited high rate of set-up during the initial restrikes. The rate of set-up became slower once the excess pore water pressure was dissipated.

Logarithmic rate of set-up parameter "A" was back-calculated for individual soil layers for two initial normalized time (i.e, t_o = 1 hour and i.e, t_o = 1 day). The unit side resistance (f_s) was used in this study instead of the total resistance (R_t) or side resistance (R_s) to evaluate set-up behavior. A total of 94 pile segments were considered in this study and clayey soil behavior was dominant on 70 soil layers. The corresponding average values of the rate of the set-up parameter (A) for clayey and sandy soil layers were 0.58 and 0.28, respectively, for initial normalized time, t_o = 1 hour; and for t_o = 1 day the average values of the rate of the set-up parameter (A) for clayey and sandy soil layers were 0.31 and 0.15, respectively.

The magnitude and rate of set-up were found to correlate with the different soil properties. The undrained shear strength (S_u), plasticity index (PI), coefficient of consolidation (c_v), sensitivity (S_t) and overconsolidation ratio (OCR) have significant influence on the set-up parameter "A." The set-up parameter "A" was found to decrease with increasing S_u, c_v, and OCR, and to increase with increasing PI and S_t. Multivariable non-linear regression empirical models were developed to estimate the increase of unit side resistance (f_s) with time (or set-up) for individual clayey soil layers.

Reliability-based analyses using FOSM, FORM and Monte Carlo Simulation were performed to calibrate the set-up resistance factors ($\Phi_{set\text{-}up}$) of the three empirical models for incorporating the effect of set-up into the LRFD pile design methodology. Four different time intervals were selected for this reliability analysis, i.e., at 30 days, 45 days, 60 days, and 90 days after EOD. The set-up resistance factor ($\Phi_{set\text{-}up}$) corresponding to a dead load to live load ratio (Q_{DL}/Q_{LL}) of 3 at a target reliability index (β_T) of 2.33 is recommended to be $\Phi_{set\text{-}up}$ = 0.35 for all time intervals.

RECOMMENDATIONS

It is strongly recommended that DOTD design engineers start implementing the proposed set-up models, especially model 1 (using both t_o = 1 hour and t_o = 1 day), and the corresponding set-up resistance factor ($\Phi_{set\text{-}up}$) in the design and analysis of piles driven in cohesive soil for all future state projects.

Several project sites need to be selected to compare between the design of pile foundations with and without considering the pile set-up to conduct a cost benefit study and to demonstrate the cost savings.

A new research project needs to be initiated to study and investigate the set-up behavior of open-ended pipe piles, develop an empirical set-up prediction model for local soil conditions, and calibrate the corresponding resistance factors for LRFD design of open ended pipe piles.

It is recommended for a workshop to be held to train DOTD engineers and local geotechnical design engineers on how to incorporate the pile set-up in the analysis and LRFD design of deep pile foundations.

A new research project also needs to be initiated that focuses on evaluating the time frame of pile set-up phenomenon using piezocone penetration and dissipation test data.