

Mobilization of Component Interface Stresses Between Soil and Pile Under Lateral Loading

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Abstract

The inelastic deformations for pile foundations under lateral loading occur below grade; therefore, the overall lateral load behavior of the system is influenced by the interaction between the shaft and the surrounding soil. This complex interaction is commonly modeled using p - y curves. The standard p - y method does not *explicitly* take into account all the key aspects of soil-pile interaction, namely the nonlinear response of the soil, frictional interface stresses between the soil and the pile, the generation of gaps between the soil and pile, damping under dynamic loads, and the structural response of the pile. Past research efforts (Nogami, et al., 1992, Boulanger, 1999, Lermite, et al., 2001) have been aimed at developing unidirectional p - y interaction curves comprised of an assembly of distinct sub-elements; the sub-elements are each in charge of modeling a specific component of soil-pile resistance under lateral loading. These assembled soil-pile interaction curves are then compared to a backbone curve based on the existing standard p - y curves. However the current models for p - y curves are calibrated primarily from lateral load tests and lump all components of lateral resistance into one curve. Thus the contribution of each sub-element to the overall assembled behavior of the interaction “ p - y ” curve becomes somewhat arbitrary. This study examines the effects of nonlinear soil resistance to relative displacements between a model pile and soil, including the effects of gapping, cyclic degradation, and interfacial slip through laboratory testing. Measurements are presented for the normal compressive soil stress on the leading face of the pile, soil/pile interface stress along the sides of the pile, and active normal soil stresses on the pile. Using current sensor technology, normal stresses in soil are measured and side-frictional interface stresses are inferred. Professor Michael O’Neill stated in his Thirty-Fourth Karl Terzaghi Lecture (O’Neill, 2001) that “the design of deep foundations is a complex matter that should be addressed in a design context by engineers who are experienced in the observation of pile behavior, theoretical modeling, and the appropriate use of design methods” – this paper attempts to stay true to Professor O’Neill’s words by applying both observations from experimental measurements and theoretical modeling to a complex topic in foundation engineering.

Introduction

A common method of analyzing pile response to applied lateral load is through finite difference or finite element modeling of the soil-pile system using a series of nonlinear spring elements along the length of the pile to model the lateral soil reaction. Current design practices model the behavior of these spring elements using predefined “ p - y curves” that provide a relationship between the soil reaction per unit length, p , and lateral displacement, y , specific to the soil type in which the pile is embedded. However, these standard p - y curves have been developed from a limited number of case histories for a narrow range of pile diameters. Furthermore, the lateral soil reaction is known to be the resultant of several primary stresses: the passive stresses normal to the leading face, the active stresses normal to the trailing face (usually deemed negligible), and the shear stresses along the sides of the pile (Fig. 1). The lumped p - y curves do not consider these components individually and, therefore, do not consider how their response and relative contribution change with variation in pile, soil, and interface properties.

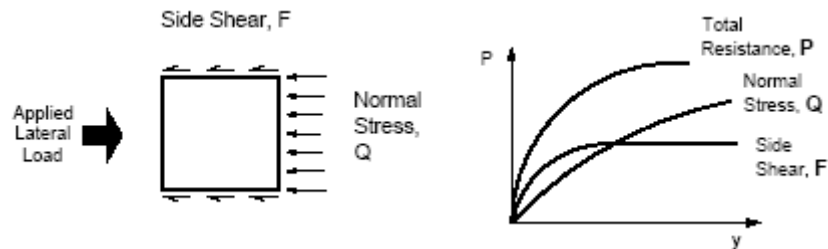


FIG. 1. The primary components of soil resistance, p (after Smith and Slyh 1986, adapted for square cross-section)

With the recent development of advanced finite element codes capable of modeling pile response to cyclic and seismic loading using complex spring and damper elements, there is a need to deconstruct the lumped p - y curves into several fundamental components in order to properly incorporate the effects of gapping, cyclic degradation, and interfacial slip. This study attempts to investigate the contribution of the passive and shear stress components through normal soil stress measurements. Total lateral soil reaction, p , profiles are determined from bending curvature measurements along the length of the pile through the use of beam theory. The passive reaction normal to the leading face of the pile is estimated experimentally using stress cell measurements, while frictional forces at the soil-pile interface are inferred through a comparison of this estimated passive reaction with the total soil reaction.

Test Details

The present study was a laboratory scale model of a single pile embedded in granular material and subjected to unrestrained lateral loading at the pile head (Whelan, 2004). Although there is debate over the continuity of stress-strain relationships between model and prototype environments, reference should be made to the conclusions of Poorooshasb (1995). The mathematical relationships presented

uphold the similarity between sand-water model and prototype systems under quasi-static loading where inertial effects are insignificant. In the present study, a 0.6604m long, aluminum 6063-T52 square hollow tube section was selected in accordance with scaling relations to model a plausible field pile under a geometric scaling factor L_p / L_m of 12, where L_p and L_m represent the lengths for the prototype and model piles respectively. The wall thickness was milled, then subsequently filed and sanded, until a uniform thickness of 0.889mm was attained and the outer width of the tube was resultantly reduced to 24.0mm. The thickness and uniformity along all four faces of the pile section were confirmed within 0.0254mm accuracy using a Positector Ultrasonic Thickness Gage.

To satisfy geometric scaling requirements and properly model the soil-pile interface behavior, a dry ground silica fine powder was selected to simulate granular material. The soil was well graded with a measured effective diameter, D_{10} , of 0.002mm and coefficient of uniformity, C_u , of 22.1. Scaled analysis of the grain size distribution classifies the model soil as a silty-sand with approximately 16% fine-grained soil by the Unified Soil Classification System. The soil was loosely deposited into a semi-rigid test container of 0.61m diameter and 0.76m height through the use of an overhead traveling pluviation system. Container walls were constructed of neoprene rubber to simulate free-field boundary conditions, while woven Kevlar bands were used to stiffen the external radial face of the column and prevent bulging. The instrumented pile was fitted with a pyramidal tip and driven into the test soil using a guide frame to assure plumbness and prevent pile rotation and horizontal translation during driving.

Unidirectional lateral loading was applied at a height of 55.9mm above the groundline by a hanging weight system. A triangular wedge attached to a miniature load cell mounted on a frictionless guide frame distributed the load across the pile width and provided for unrestrained pile head rotation. Incremental loading up to 105N was applied, resulting in a final ground line deflection of 68.6mm.

Instrumentation

Six pairs of temperature-compensated resistive foil strain gages were installed at 89mm increments down the length of the pile, beginning at the groundline location, in order to measure the pile curvature at discrete points. The gages were adhered to the interior faces of the hollow tube using a specialty insertion and clamping tool developed for the square cross-section. A series of four-point bend tests were performed and theoretical strains were compared to measured values in order to develop calibration factors for each gage for compensation of any mild axis misalignment.

The lateral displacement of the pile at the load point was measured using a captive guided Linear Variable Differential Transformer (LVDT) connected in series with the load frame. A second LVDT was fitted with an angled arm to measure the displacement 76.2mm above the load point in order to deduce the pile head rotation.

Entran EPL surface mount miniature pressure cells were placed on the leading face of the pile to measure contact soil stresses along the length and across the width of the pile (Fig 2). These sensors are strain gage based diaphragm-type stress cells with

a 172kPa pressure range in air. The 5mm diameter and 1mm height of these cells allows for minimally intrusive measurement of multiple contact pressures along the width of the pile, while satisfying dimensional recommendations for the ratio of grain size to stress cell diameter (Weiler and Kulhawy, 1982).

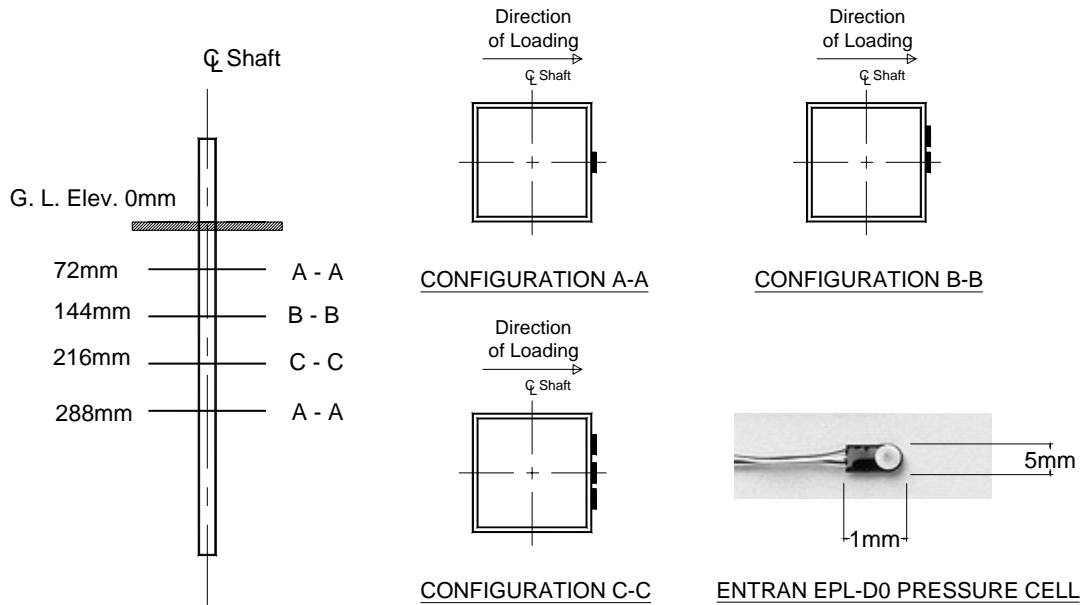


FIG. 2. Locations of Pressure Cells on Model Pile

Measurement of soil pressure using a stress cell must be performed with careful consideration of the parameters that will affect the performance of such a cell during the experimental procedure. Since soil exhibits a nonlinear stress-strain relationship that is dependant on mechanical properties of the soil, pre-loading history, principle stresses, void ratio, and pore water, it is not only impractical, but impossible to design an ideal pressure cell that has the same stress-strain relationship as the soil in which it is embedded. Resultantly, any stress measurement obtained with a pressure cell will be inconsistent with the free field soil stress (Weiler and Kulhawy, 1982). Additionally, even though minimally intrusive miniature pressure cells have been selected, the simple presence of these sensors on the face of the pile modifies the three-dimensional soil-pile interface and disrupts the natural distribution of soil stress that would occur on an undisturbed interface. As a result of the protruding nature of the cell, free-field lateral stress rotation occurs and typically additional stress acts normal to the face of the pressure cell, thus over-registering the local stress (Weiler and Kulhawy, 1982).

Stress Cell Calibration

A calibration chamber was developed similarly to the one proposed and evaluated by Selig et al. (1997), though reduced dimensionally for miniature pressure cells (Fig. 3). The chamber was 152mm in diameter, 102mm in height, and featured a side wall

lined with a double layer of latex sheeting coated with Talcum powder between layers to reduce the effects of friction between the rigid wall and the sand particles. The stress cell was adhered to a small section of aluminum square tubing identical to the test pile and placed facing upward in the chamber. The remainder of the container was then filled with the model sand and carefully compacted to the desired density to prevent damage to the sensor. After the surface was leveled, two sheets of 0.8mm neoprene rubber were placed over the container. Controlled development of pressure on the sand surface was applied through an inlet at the center of the sealed lid and the soil pressure acting on the stress cell was assumed to be equal to the air pressure above the neoprene membrane provided a slow rate of pressure development.

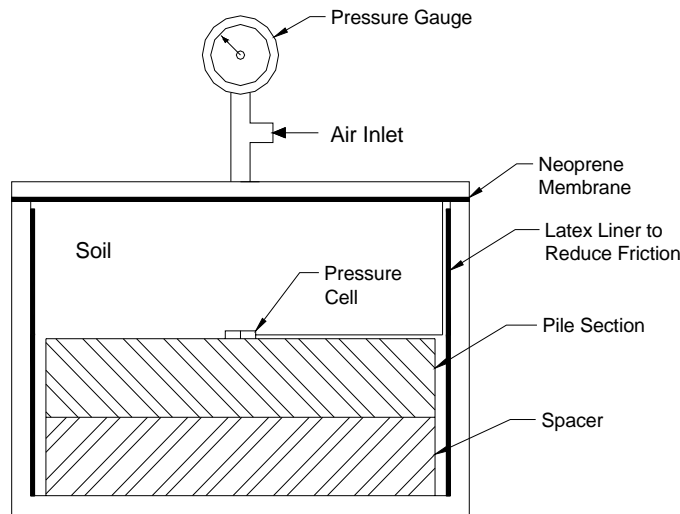


FIG. 3. Schematic of Calibration Chamber

Since no precise in-situ density measurement was obtained for the pluviated test sand, several calibration tests were performed in loose to medium-loose ground silica over the range of stress cell voltage output exhibited during lateral load testing. The calibration tests were consistent and indicated that the stress cells exhibit a significant over-register of soil pressure if factory calibration is employed when converting voltage measurements to pressures (Fig. 4). The calibration measurements were then averaged and fitted with a third order polynomial to define the gage response in the test soil.

Soil-Pile Interaction Behavior from Present Test

A weighted residuals method (Wilson, 1998) was used to double differentiate the discrete moment data and the resulting nodal values of soil reaction for each element were averaged and assigned to the central location of the element. These values were then fitted with a fifth-order polynomial to define the soil reaction profile along the length of the pile (Fig. 5). This method was found to reduce the error in closed-form differentiation of polynomial fits of test data, in particular at the boundaries where drastic concavities were produced. The shape and cross-over locations of the soil

reaction profiles agree well with a general distribution established in other research utilizing miniature pressure cells on a rigid pile embedded in cohesionless material and subjected to lateral loading (Prasad, 1999).

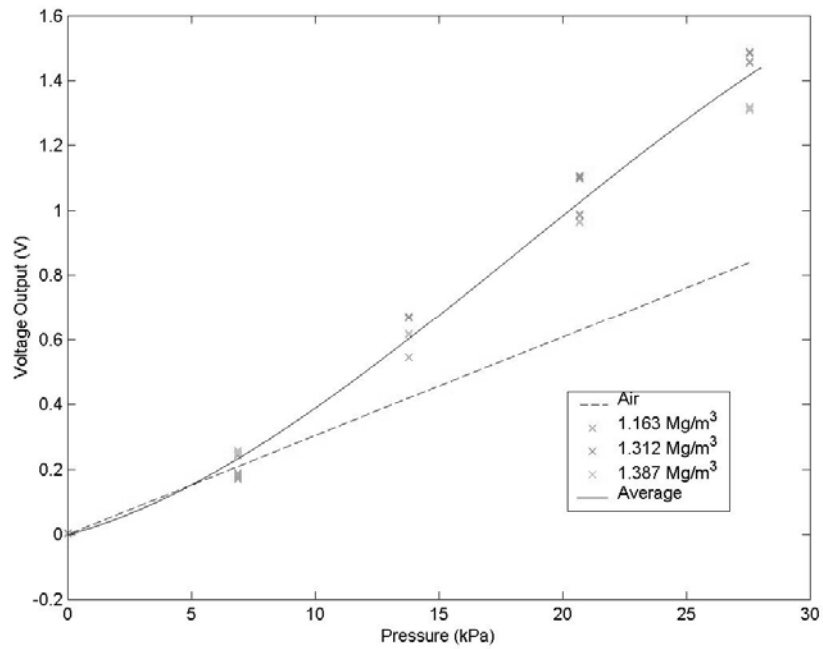


FIG. 4. Soil Stress Cell Calibration Results

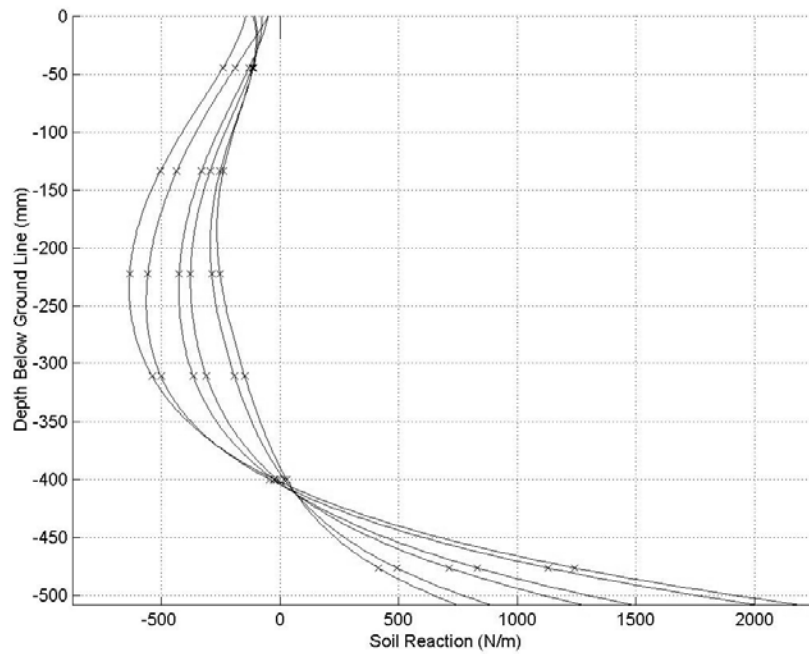
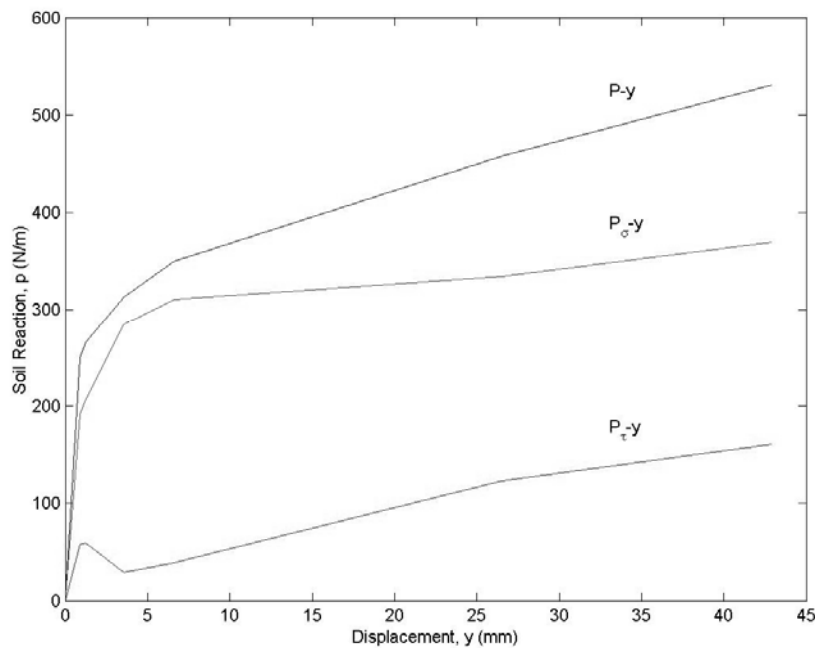


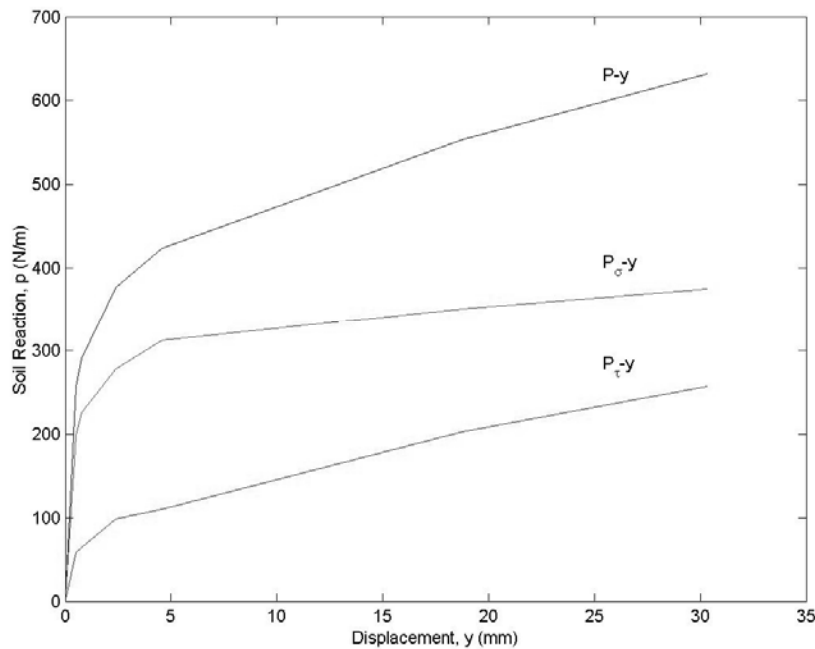
FIG. 5. Soil Reaction, p , Distribution Profiles

The pile curvature data was integrated twice, using pile head slope and ground line deflection as integration constants, to develop profiles of the pile displacement at each load increment. Excessive compliance in frame connecting the pile to the LVDT used for rotation measurement dictated the implementation of an iterative revision of the pile head slope inputs to force each displacement crossover depth to coincide with the crossover location in the corresponding soil reaction profile. The magnitude of the fairly low curvature measurements and shape of the back calculated deflection profiles indicate that the pile response was semi-rigid in nature, which is attributed to the loose condition of the test soil.

Although p - y curve generation and subsequent analysis is not implemented in the design and analysis of rigid piles, the presence of bending curvatures in semi-rigid piles offers the unique opportunity to investigate the soil-pile interaction behavior through generation of p - y curves common to flexible piles. Distributions of soil pressures across the diameter of the pile at the two locations with multiple stress cells did not indicate a clear trend. Furthermore, finite-element analysis of a square cross-section laterally displacing through an elastic medium suggests only a slight increase of normal pressure with distance from the central axis (Baguelin, 1977). Consequently, stress cell measurements at each of these locations were averaged and multiplied by the pile diameter to estimate the contribution of the passive reaction normal to the pile width, p_{σ} , to the overall lateral soil reaction, p . Since active pressures on the trailing face of a laterally loaded pile are typically negligible, the difference between p and p_{σ} can be attributed to the side shear forces, p_{τ} , on the soil-pile interface. To examine the relative contribution of the component reactions to the total lateral soil response, passive reaction, p_{σ} , as well as side friction, p_{τ} , forces versus pile displacement, y , curves were produced and plotted against the p - y curves developed for each of the locations of multiple stress cells (Fig. 6a, b).



a) 6 Diameter Depth



b) 9 Diameter Depth

FIG. 6. P-y Decomposition at Stress Cell Locations

To further illustrate the magnitude and development of the normal and side shear stresses during one-way loading, the ratio of p_{σ} to p is plotted against the displacement level for the two depths in Fig. 7. The results indicate that the passive normal soil stress contributes approximately from 77% to 90% of the total soil reaction at low displacement. As deflection increases, a nonlinear decrease in the relative contribution of the normal component occurs and at higher displacement levels accounts for only 60% to 70% of the total soil reaction.

This observation may suggest that the passive normal resistance dominates the lateral soil reaction for a square cross-section pile embedded in cohesionless material, though at increasing levels of displacement the side frictional contribution accounts for a substantial fraction of the p . This is contrary to the soil-pile interaction behavior for rigid as well as flexible circular shafts embedded in cohesive material observed experimentally by several authors in the past (Janoyan, 2001 and Smith, 1986). Both authors had concluded that the stress normal to the pile modestly contributes within the range of 15%-25% of the lateral reaction at low-level displacement and disproportionately builds to about 45%-50% near failure. Additionally, side shear was found to rapidly mobilize to an ultimate resistance for cohesive soils, while this research suggests that the mobilization of side friction may occur more gradually in cohesionless soils and may not peak to an ultimate value under working loads.

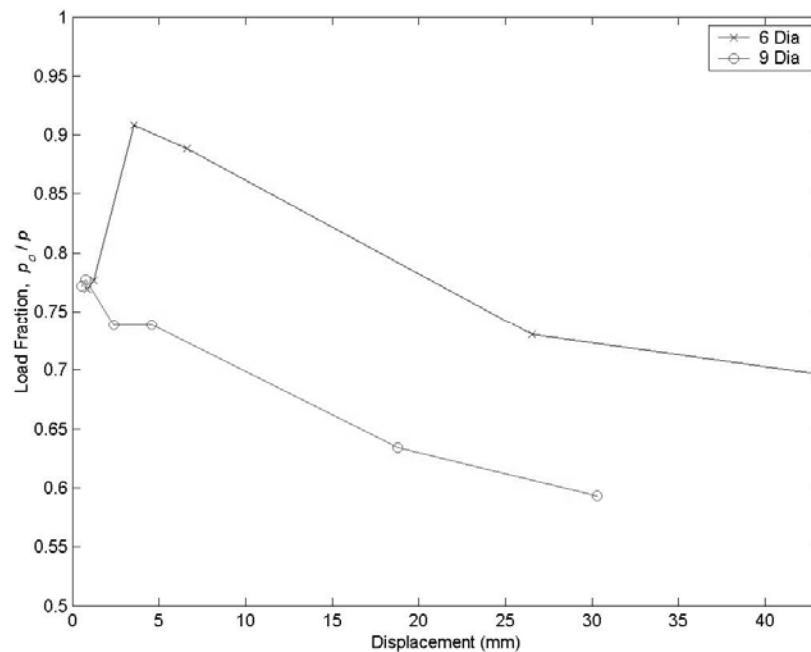


FIG. 7. Relative contribution of passive normal reaction, p_o , to the total soil reaction, p , as a function of deflection at 6 diameter (144mm) and 9 diameter (216mm) depths.

Conclusions

In this study, the development of p - y curves typically used for the analysis of flexible piles was advantageously utilized to investigate the soil-pile interaction behavior of a semi-rigid square test pile. Comparison of the total lateral soil reaction, p , values obtained from application of beam theory to strain measurements to component resistances inferred from miniature contact stress cell measurements was undertaken in an effort to investigate the mobilization behavior and relative contribution of passive normal and side frictional forces to the lateral soil reaction.

The passive forces normal to the leading face of the pile were found to dominate the overall p - y response during the lab-scale testing study. However, as deflection increased and the passive pressures approached their ultimate values, side friction continued to mobilize and could account for a substantial 30% to 40% of the total reaction. These results indicate a significant deviation with soil-pile interaction behavior observed experimentally for circular shafts embedded in cohesive soil. Consequently, further investigation into the mechanics of passive and shear stress development on laterally loaded piles and construction of the current lumped p - y design curves may be justified.

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