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IMPACT OF SHEAR-FLEXURE INTERACTION ON P-Y CURVES OF PILE FOUNDATIONS

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ABSTRACT

The nonlinear behavior of the *p-y* curves is largely dependent on the structural pile properties, the shaft boundary conditions and the soil type. Typically, test results are used to derive *p-y* curves through double integration and double differentiation of pile curvature measurements and moment profiles, respectively. While this procedure is suitable for shafts with flexure dominant failure (e.g. piles with free-head boundary conditions), it may not accurately represent the response of reinforced concrete piles with fixed head (top rotation restrained) boundary conditions. To study this problem, a coupled shear – flexure interaction model for axial-bending-shear behavior coded in OpenSees is applied to a 0.61 m flagpole and a 0.61m fixed head pile specimen to investigate the possible influence of shear deformations on pile responses. The pile sections are modeled using a fiber model in which shear-flexure-interaction is captured on a macro element level by using a biaxial constitutive model for reinforced concrete. The surrounding soil is represented by *p-y* curves derived from large scale pile tests with similar boundary conditions. Analysis results show that for flagpole piles, shear forces and shear deformations are negligible; however, shear deformations contributed up to 40% to lateral displacements for the fixed head pile. Results suggest that nonlinear shear deformations for reinforced concrete piles should be considered for fixed-head or similar conditions, and that an appropriate sensor layout should be used to capture shear deformation when deriving *p-y* curves from field measurements.

Introduction

Soil structure interaction significantly influences the lateral behavior of pile bridge foundation systems subjected to earthquake loading. Simplified modeling approaches for these complex soil-structure systems include rigid pile analyses, depth to pile fixity analyses, whereas the current approaches typically focus on the use of finite element models, strain wedge models, and pile nonlinear beam-column models with accompanying soil *p-y* springs. P-y springs, representing the soil resistance *p* per unit length along the pile as a function of pile displacement *y*, are mathematically described using cubic parabolic expressions such as shown in Equations (1) as example of the most commonly used *p-y* curves for stiff clay by the American Petroleum Institute (API 1993).

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$$p = 0.5p_u \left(\frac{y}{y_{50}} \right)^{1/4} \quad (1)$$

where, p_u denotes the ultimate soil resistance and y_{50} is the deflection at $0.5p_u$, determined through laboratory triaxial testing, y_c is the deflection at soil resistance p_u corresponding to the strain from the laboratory soil stress-strain curve. *P-y* curves derived from large scale experiments require curvature measurements obtained from sensors such as strain gauges (SGs), Linear Variable Differential Transformer (LVDTs), Fiber Optic Sensors (FOS), or Tiltmeters that provide average strain or rotation readings over respective gauge lengths. Curvature values are used to determine moment values using pile section-specific moment versus curvature (*M-Φ*) relations. Traditionally, linear *M-Φ* relationships are used with the assumption all pile deformations are associated with flexural deformations, (i.e. *p-y* curves used by the American Petroleum Institute [API, 1993]). Although, nonlinear *M-Φ* relations have been used in some cases (Wallace *et al*., 2001), most traditional *p-y* curves do not account for *EI* variation over the pile height based on the level of pile deformation. Curvature and moment profiles obtained along the pile height are then differentiated and integrated to obtain *p* and *y* profiles along the pile depth, which can be further assembled as *p-y* curves for specific pile depths.

Impact of Pile Boundary Conditions

Figure 1 shows two representative boundary conditions for common bridge foundation piles. Two extreme pile ground-line boundary conditions can be distinguished: A flagpole condition with no rotation restraint at the pile top, and a fixed head condition in which the pile rotation is restricted by connecting the pile to a cap at ground line. Flagpole piles are allowed to rotate and typically fail by forming a single flexural yielding section (plastic hinge) while piles that are connected to pile caps experience less rotation at ground-line, but fail under double curvature pile bending characterized by two possible yielding locations and higher moment gradients.

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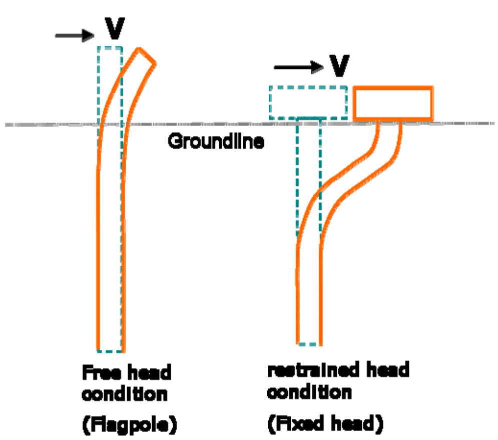


Figure 1.Typical pile boundary conditions

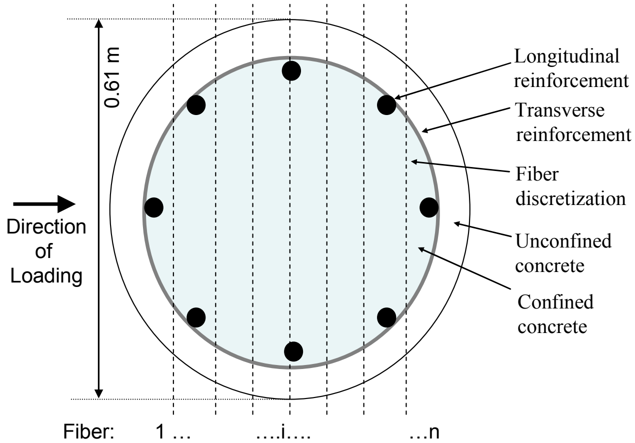
P-y curves derived from prior studies (Stewart *et al.* (2007)) on piles with both boundary conditions, namely a 0.61 m reinforced concrete flagpole pile and a 0.61 m RC fixed head pile revealed higher stiffness (~2 times) and higher capacity (40-50%) for the fixed head pile as compared to the flagpole. This comparison suggests that boundary conditions significantly influence pile *p-y* curves. The larger moment gradients observed in fixed head piles may also lead to higher pile shear forces and shear deformations which are not considered in traditionally conducted p-y analyses. In order to measure shear deformations experimentally, prior studies have shown that a more comprehensive sensor layout; i.e. diagonal sensors along with longitudinal sensors, is needed to capture and separate deformations resulting from flexure and shear. While fixed head shafts responses may be significantly impacted by the effect of pile shear deformations and shear forces, for flagpole shafts, which are dominated by flexural behavior with relatively small moment gradients (e.g., slender elements with relatively low shear stresses), the interaction between nonlinear axial-bending behavior and shear behavior is likely to be unimportant.

Objectives and Analytical Approach

The objective of this study is to use analytical tools to assess the potential impact of nonlinear shear deformations on *p-y* curves by assessing the relative contribution of shear and flexure deformations to pile displacement and force profiles over the pile height. To accomplish this, two different modeling options for reinforced concrete piles are used along with *p-y* curves to study the lateral load behavior of reinforced concrete piles embedded in stiff, clayey soil. Instead of using arbitrary pile sections and soil properties, pile tests conducted by Stewart *et al.* (2007) are used as a basis for this study. Advantages of implemented test characteristics include the use of experimental *p-y* curves that were derived for the specific head boundary conditions and the ability to compare model results such as pile load deflection relationships with test results. It is important to mention that the implemented *p-y* curves by Stewart *et al*. (2007) were not derived following the traditional double integration and derivation process but are a result of an alternative fitting procedure in which the functional form of the API *p-y* curves were calibrated to match the field curvature and moment profiles along with the oval load displacement backbone relationship. This procedure along with the developed *p-y* curves is described in detail in Stewart *et al*. (2007) and Khalili-Tehrani (2009).

Analytical Model

The analytical studies were performed using the finite element program *OpenSees* (http://peer.berkeley.edu/OpenSeesNavigator/) provided by the Pacific Earthquake Engineering Research center (PEER). The analytical model was originally developed by Massone *et al.* (2006) to examine the interaction of shear and flexural forces and deformations of reinforced concrete walls (Massone *et al*. 2009). For the current study the model was modified and applied to reinforced concrete piles. As mentioned before, the study uses the two specimens (flagpole and fixed head) implemented in two different analytical sub-models: (1) one that incorporates nonlinear axial-bending behavior, referred to as an uncoupled model, and (2) one that considers interaction between axial-bending behavior and shear behavior, referred to as a coupled or shear– flexure interaction model. Both models are used to investigate response profiles over the pile height for lateral displacement, moment, and shear for both the flagpole and fixed-head configurations to assess the potential impact of shear-flexure interaction on *p-y* curves. The section and material models of the analytical model are calibrated to match the in situ material characteristics of the large scale test specimens. The cross-sectional properties of the flagpole and the fixed head shafts are identical and consist of 0.61 m diameter reinforced concrete shafts. In the analytical model, the pile shafts are represented using a fiber model consisting of 8 fibers as shown in Figure 2. Each fiber was defined through a coordinate location, a fiber area and the respective material properties. Concrete was represented using a uniaxial material model, with confined and unconfined concrete sections as shown in Figure 2. Unconfined concrete areas were assigned an average compressive strength f'_c of 38 MPa, at a concrete strain ε_c of 0.0025 and f'_c of 32 MPa, at a concrete strain ε_c of 0.0023, for the flagpole and fixed head cases, respectively. Confined concrete characteristics were determined using the Saatcioglu and Razvi (1992) relationship resulting in a confined compressive strength f'_{cc} = 56 MPa at a confined concrete strain ε_{cc} = 0.0084 and f'_{cc} = 51 MPa, at concrete strain ε_{cc} = 0.0089, for the flagpole and fixed head cases, respectively. Since the analytical model for concrete considers the effects of biaxial compression softening, the effect of tension stiffening in the stress-strain behavior of concrete is incorporated by using the average (smeared) stress-strain relationship proposed by Belarbi and Hsu (1994). The reinforcement steel is modeled using the Menegotto-Pinto (1973) relationship updated with parameters proposed by Belarbi and Hsu (1994) to account for the softening of the rebar stress strain relationship when strains are concentrating in steel at concrete crack locations. Based on these adjustments, the reduced yield stress for the longitudinal reinforcement was taken as 427 MPa and 439 MPa for the flagpole and fixed head shaft, respectively, with a post yield strain hardening ratio of b = 0.008, with b describing the ratio between initial and post yield stiffness. The material properties for the transverse reinforcement were assumed to be identical to those for the longitudinal reinforcement. Longitudinal reinforcement of both piles consisted of 8#9 bars (d_b = 29 mm). Transverse reinforcement was installed as 48 cm diameter spirals made of #5 bars (d_b = 16 mm) spaced at 11 cm pitch over the length of the pile. The cross-sectional and vertical model discretizations are shown in Figure 2 and 3, respectively. In both cases lateral load is being applied at the top of the pile.



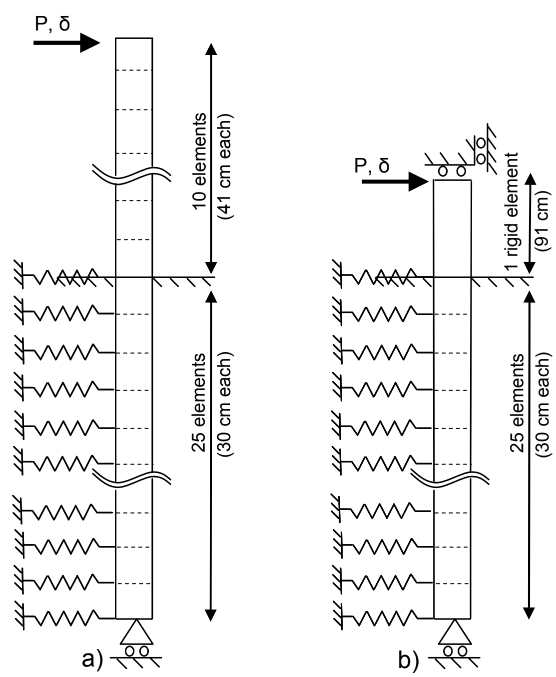


Figure 2. Fiber model of pile cross-section **Figure 3. Model Discretizations for both piles.**

The shear flexure interaction model

The macroscopic fiber model uses shear springs assigned to each macro fiber element (shown in Figure 2), which in turn was treated as a RC panel element subjected to in-plane uniform normal and shear stresses, together with the assumption that the resultant horizontal normal stresses are zero. Therefore shear-axial interaction is incorporated at a fiber level, which in turn results into shear-flexure interaction at the element level. The constitutive stress-strain model for concrete is applied along the principal directions to obtain the stress field associated with the principal strain directions, assuming that the principal stress and strain directions coincide (Modified Compression Field Theory (MCFT) by Vecchio and Collins (1986), Rotating-Angle Softened-Truss-Model (RA-STM) by Pang and Hsu (1995)). Since axial and shear response of each fiber panel are coupled, interaction is provided for the overall model. Massone *et al*., (2006) presents a detailed model formulation along with in-depth descriptions of the implemented iterative procedures to solve for element strains, stresses and forces.

Results

Force Displacement Relationships

Load displacement responses of the model pile and experiment are shown in Figure 4 and 5 for the fixed head and flagpole pile respectively. The model load displacement response for the flagpole pile is almost identical for the flexure and shear flexure model, hence only one curve is shown in Figure 4. This is expected, since the pile is slender and shear deformations are small. The pile model matched the maximum field lateral force of about 125 kN.

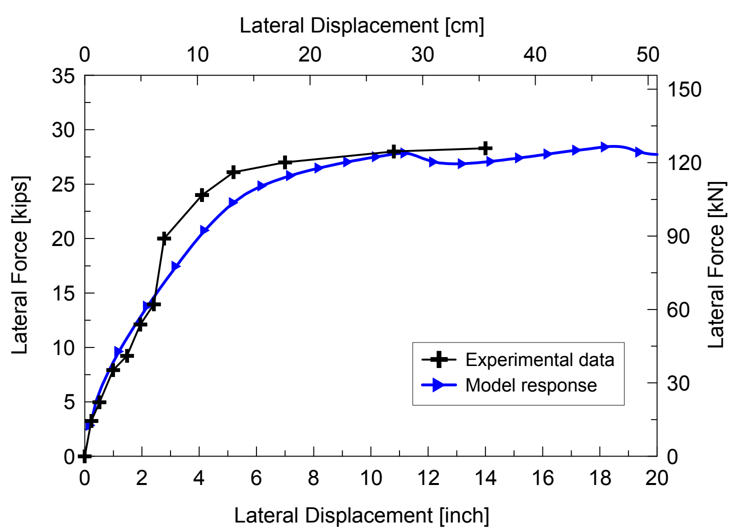


Figure 4. Model and experimental load displacement responses for the flagpole pile

For the fixed head pile (Figure 5), the "flexure - only" model matches the experimental results with respect to initial stiffness very well and captures the maximum lateral experimental force of about 1214 kN at a displacement of 5 cm. Only slight overestimation of the ultimate capacity of the model response is observed which was expected given the approach used to derive the *p-y* relations (i.e., the assumption that all deformation are solely a result of flexural deformations). The coupled- or shear–flexure interaction model matches the initial stiffness but underestimates the ultimate capacity by 10%. Pile failure is observed for the shear-flexure interaction model at a lateral displacement of 11.5 cm while pile failure during the experiment occurred at a lateral displacement of about 7.5 cm. Since transverse reinforcement plays a significant role in transferring shear forces and providing lateral confinement, parametric studies were conducted in which the confinement was reduced by 50%, i.e. only 50% of the area of transverse reinforcement was used to determine the confined stress - strain response , while the quantity of transverse reinforcement in the model was unchanged. Results for this case reveal a much faster drop in the lateral load of approximately 1050 kN at a lateral displacement of 7 cm. This result matches the test results with respect to failure initiation and indicates that the influence of shear forces and deformations are significant and required accurate capturing in the analytical modeling approach. Since the same *p-y* relations were used for the flexure only and the coupled model, by assuming that the coupled model reasonable represents the nonlinear behavior of the reinforced concrete pile, results imply that *p-y* curves derived by Stewart *et al*. (2007) are too soft. *P-y* curves needed to replicate the experimental load displacement response will most likely be stiffer and possibly stronger.

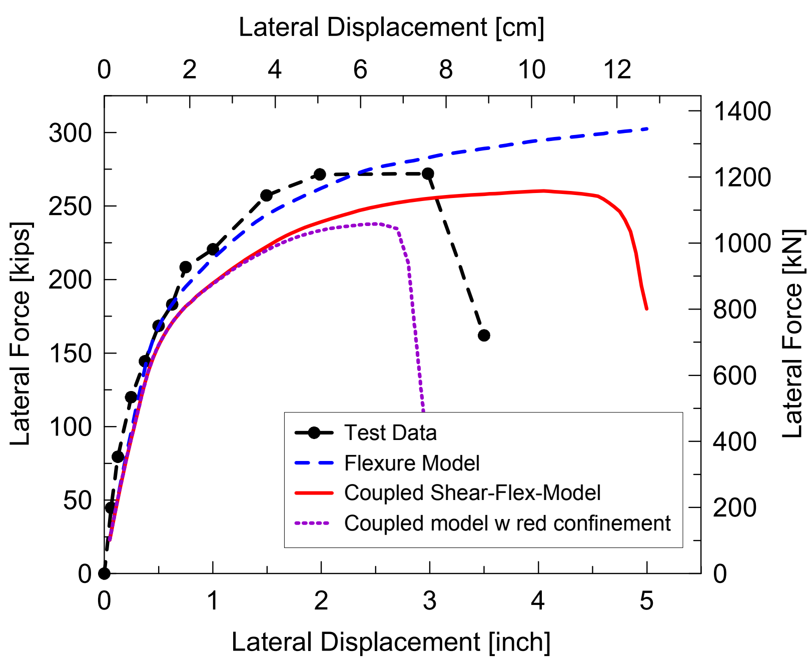


Figure 5. Model and experimental load displacement responses for the fixed head pile

Displacement Profiles

The flexural, shear and total lateral pile deformations were obtained for both the flagpole and fixed-head conditions at various lateral top displacement levels using the shear-flexure interaction model (Figure 6 and 7). Shear deformations were acquired directly from the analytical model and flexural deformations were calculated by subtracting the shear contribution from the total pile deformation. Figure 6 shows that the overall response of the flagpole pile is flexure-dominated and that shear displacements are negligible (< 0.05 cm). Flagpole flexural bending deformations are primarily taking place in the shaft sections extending above ground line (Figure 6), whereas the largest shear deformations occur just below ground line and drop to near zero at 150 cm above and below ground line. However, shear deformations contribute less than 0.1% to the maximum lateral top displacement of 51 cm.

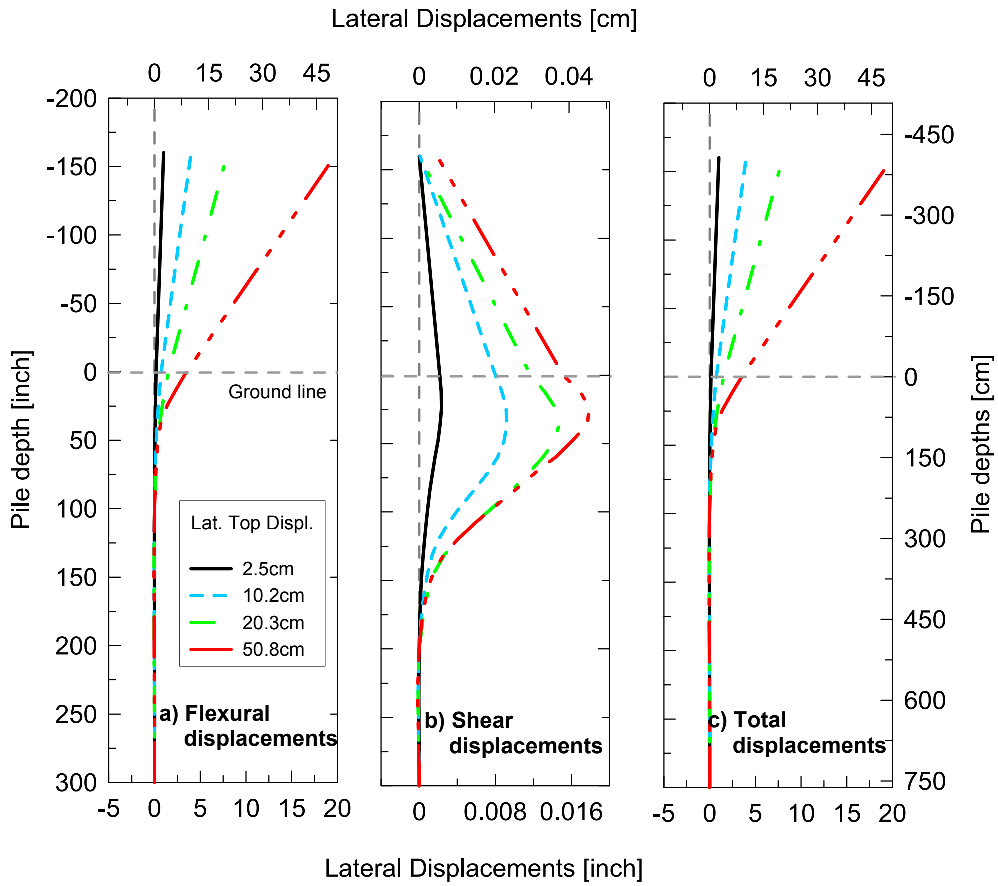


Figure 6. Flexural, shear and total pile deformations for the flagpole pile

For the fixed head pile (Figure 7), shear deformations (Figure 7b) are much larger (up to 200 times) than for the flagpole pile, and contribute up to 40% to the total pile lateral displacements. Shear deformations are concentrated right below ground line (up to about 60 cm depth) and are nearly zero at other locations. Flexural deformations are observed between ground line and a pile depth of 240 cm (~4d), and account for up to 60 % to the total displacements. At lateral top displacements exceeding approximately 5 cm, flexural displacements increase by only small increments (Figure 7a) while shear deformations become large, indicating that the loss of lateral strength is associated with shear failure. In contrast to the large impact of shear deformations on the overall deformation profile, shear forces were found to have much less influence on the pile response (Lemnitzer 2009).

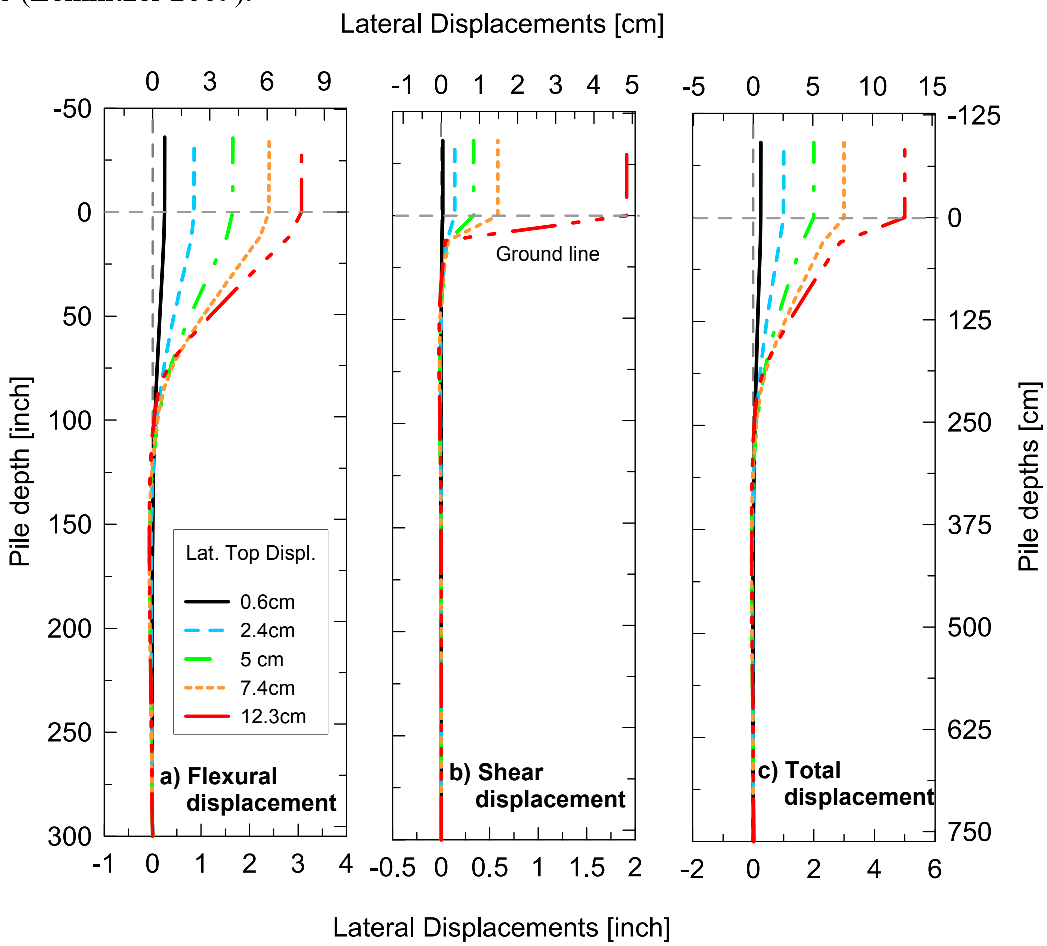


Figure 7. Flexural, shear and total pile deformations for the fixed head pile

Conclusions

A flagpole pile and a fixed head pile were modeled using OpenSees to investigate the effects of shear-flexure interaction on the pile response. Pile configurations and material properties were calibrated to match parameters used in a previous experimental study of large scale pile foundation systems. In this study, piles consisted of 0.61 m diameter reinforced concrete shafts with flagpole and fixed head boundary conditions. The analytical model is based on a fiber model with uniaxial material models for concrete and reinforcement. The coupled shear-flexure model works on a macroelement level by defining RC panel behavior on a displacement-based column type element. The soil is modeled using pile specific p-y curves for the two boundary conditions. For a flagpole configuration, the impact of shear-flexure interaction was expected to be small, whereas for a fixed-head configuration, more significant interaction was anticipated. Results confirmed that for the flagpole pile shear deformations were insignificant, contributing less than 1% of to the peak lateral displacement of 51 cm. The model response showed nearly identical results in the overall top load displacement relationship between the flexure only and the coupled shear-flexure interaction model. Therefore, p-y curves derived from tests of flagpole pile configurations are unlikely to be influenced by interaction between axial-bending and shear behavior. For the fixed head specimen, however, results indicate that shear deformations significantly influence the overall top load displacement response for displacements exceeding 0.6 cm. Shear deformations along the pile depth for the coupled model were found to account for up to 40% of the total lateral deformations and reached their maximum contribution (analytically) at the top load displacement level for which significant lateral strength degradation was observed experimentally, hence providing a good correlation between in-situ pile behavior and model findings. The coupled model underestimates the lateral top load at lateral displacements exceeding 2.5 cm by approximately 10% because the *p-y* curves used in this study were calibrated to provide a good fit for an uncoupled model. The obtained results provide a good basis for future studies in which existing p-y curves can be recalibrated to account for the effect of shear flexure interaction.

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